A Novel Algorithm to Estimate Solar Irradiance of Urban Buildings for Photovoltaic Potential Estimation System Using a 3D City Model

Ryuji Matsuoka [1], Takashi Takemoto [1], Genki Takahashi [1], Tomoaki Inazawa [1], Shinichiro Sogo [1]

[1] Kokusai Kogyo Co., Ltd., 2-24-1 Harumi-cho, Fuchu-shi, Tokyo 183-0057, Japan - {ryuji_matsuoka, takashi_takemoto, genki_takahashi, tomoaki_inazawa, shinichiro2_sogo}@kk-grp.jp

Keywords: solar irradiance, estimation algorithm, urban building, 3D city model, photovoltaic potential

Abstract

Photovoltaic (PV) power generation is one of most promising means to prevent global warming in the present Japan. Since solar panels mounted on building façades are expected to come into wide use in urban areas, accurate estimation of PV potential of building façades is necessary for urban energy management planning. Accordingly, we decided to develop a system to estimate PV potential of urban buildings using a 3D city model. The system has two significant features: rapid estimation of hourly solar irradiance of points densely distributed on a building surface, and more flexible estimation of PV potential considering an arrangement of solar panels on a building surface. The paper reports our newly developed algorithm to estimate solar irradiance of urban buildings. The algorithm adopts the idea that “whether the sun can see us or not” indicates “whether we have sunshine or not” for calculation of hourly solar irradiance of a point on a building surface. In estimation of solar irradiance distributions on roofs and façades, utilization of projection images viewed from the sun created by using computer graphics (CG) techniques such as the depth buffer (Z-buffer) algorithm makes our system have much less computation time than most of existing systems using a hemispherical viewsheds or ray tracing. Results of an experiment conducted in Yokohama of Japan demonstrate that the algorithm would be able to estimate solar irradiance on not only roofs but also façades of urban buildings using a 3D city model accurately enough.

1. Introduction

Recent global climate changes urge us to utilize renewable energy. Photovoltaic (PV) power generation is one of most promising means to prevent global warming in the present Japan. We have already been installing many solar panels on places suitable for panel mounting such as ground surfaces and rooftops of buildings. However, since Japan is a small and mountainous country, we would be required to plan to utilize façades of urban buildings as a mounting platform of solar panels in the near future. Additionally, the recent development of light-weight perovskite solar cells encourages utilization of façades of urban buildings. Therefore, we should estimate PV potential of both roofs and façades of buildings for urban energy management planning.

Estimating PV potential of building roofs and façades would require a 3D city model. 3D city model data in some Japanese cities are currently provided by the Project PLATEAU, of which is a project started by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT) in 2020. The project aims to construct 3D city models as a platform of urban activities, provide 3D city model data as open access data, and promote utilization of 3D city models (MLIT, 2024).

There are several systems which have capability of PV potential analysis at city districts level using a 3D city model in Europe. On the other hand, the first Japanese project to estimate PV potential at city districts level using a 3D city model data in level of detail 2 (LOD2) provided by the Project PLATEAU was reported in March of 2022 (MLIT, 2024). Figure 1 shows the estimation results of solar irradiance of building roofs by the project. Since the project utilized the ESRI ArcGIS Pro which is unable to estimate PV potential of a point on a steep incline, PV potential of building roofs except façades was estimated in the project. There has been no report to estimation of PV potential of building façades using a 3D city model in Japan.

Figure 1. Japanese first estimation results of solar irradiance of building roofs by using a 3D city model (MLIT, 2024)

Therefore, we decided to develop a system to estimate PV potential of building roofs and façades using a 3D city model. The system has two significant features: One is rapid estimation of hourly solar irradiance of points densely distributed on a building surface. The other is more flexible estimation of PV potential considering an arrangement of solar panels using dense solar irradiance distribution on a building surface.

The paper reports the outline of the newly developed algorithm to estimate solar irradiance distribution on a surface of urban building. Moreover the paper reports an experiment using a 3D city model of the Minato Mirai 21 and its surrounding area in Yokohama, Japan for evaluating the validity of the algorithm.

2. Existing systems

There is no system to estimate PV potential of both building roofs and façades using a 3D city model in Japan, while there are several systems which have capability of PV potential analysis at city districts level in Europe. Three systems by using CityGML data developed in Europe are briefly reviewed from the point of view of the algorithm for determination of sunshine existence of a surface point to calculate solar irradiance and the algorithm for calculation of solar irradiance of a surface point.

https://doi.org/10.5194/isprs-annals-X-4-W4-2024-115-2024

2.1 SimStadt (SimStadt, 2024, Nouvel et al., 2015, Rodríguez et al., 2017)

SimStadt is the name of an urban simulation environment developed at the Hochschule für Technik Stuttgart (HFT Stuttgart) in Germany. The SimStadt can use data of a real urban planning situation or planning state for energy analyses of buildings, city quarters, whole cities and even regions. The application scenarios of the SimStadt range from high-resolution simulations of building heating requirements and potential studies for photovoltaics to the simulation of building refurbishment and renewable energy supply scenarios. The SimStadt was utilized in the energy analyses of the following cities: Ludwigsburg (Germany), Moabit (Germany), Zwiefaltendorf (Germany), Weddingstedt (Germany), and Wesertal (Germany).

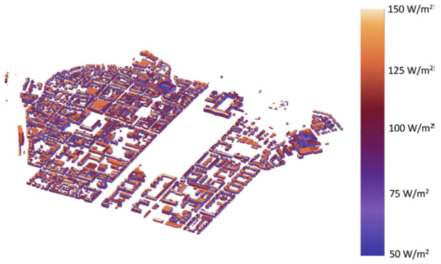


Figure 2. Example of solar irradiance map estimated by the SimStadt (Nouvel et al., 2015)

2.1.1 Determination of sunshine existence: Determination of sunshine existence in the SimStadt taking shading of surrounding buildings into account is basically conducted by ray tracing. To detect shadow the ray from the sun to a point of interest on a surface is examined whether the line intersects another object (Alam et al., 2013).

2.1.2 Calculation of solar irradiance: In calculation of solar irradiance in the SimStadt one can select one among the following sky models (SimStadt, 2024):

1) The Hay sky model, calculated with the INSEL: fast, without shadows
2) The Perez sky model, calculated with the INSEL: fast, more detailed and possibly more accurate than Hay, without shadows
3) The Perez sky model, calculated with the Simplified Radiosity Algorithm (SRA): can be very slow, should not be used for larger models, with shadows
4) The Perez sky model, calculated with the SRA on tiles: can be used for larger models (which will be split in smaller tiles), with shadows
5) The Perez sky model, calculated with the SRA on a geodesic dome: fast, can be used for comparisons with other the SRA calculations, without shadows

The SRA utilized in the SimStadt was proposed by Robinson and Stone (Robinson and Stone, 2005). Either the Hay sky model (Hay, 1976., Hay and McKay, 1985) or the Perez sky model (Perez et al., 1987) is utilized to calculate diffuse irradiance. Using the former makes less computation time, but the accuracy of estimated irradiance is lower, while the latter provides more accurate estimation results with more computation time. Parameters of either model are determined by a weather database such as PVGIS (PVGIS, 2024), INSEL (INSEL, 2024), or by using Meteonorm weather files given by a user.

2.2 virtualcitySOLAR (virtualcitysystems GmbH, 2024, Chaturvedi et al., 2017, Willenborg et al., 2018)

The prototype of the virtualcitySOLAR was developed by the Technische Universität München, in Germany, and the virtualcitySOLAR has currently been updated by the virtualcitysystems GmbH, Germany. The virtualcitySOLAR is utilized to estimate monthly measurements of direct, diffuse, and global solar irradiance on the roofs and exterior walls of buildings in 3D solar potential analysis as one of the solutions of the virtualcitysystems GmbH. The virtualcitySOLAR was utilized in the analyses of London Borough of Barking and Dagenham (UK), Helsinki (Finland), and Rennes (France).

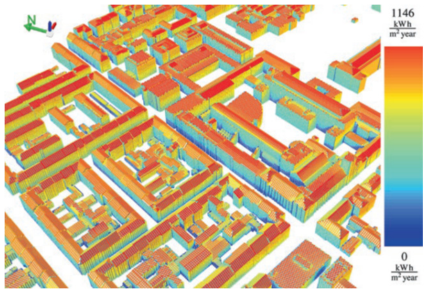


Figure 3. Example of solar irradiance map estimated by the virtualcitySOLAR (Willenborg et al., 2018)

2.2.1 Determination of sunshine existence: At the first in determination of sunshine existence the virtualcitySOLAR establishes a hemisphere which is approximated by a set of uniform spread points. For each building point a line of sight is generated to each hemisphere and sun point. These three-dimensional lines are checked for 3D-intersections with the surrounding topography to determine shadowed areas at the considered points of time by the ray tracing method proposed by Möller and Trumbore (Möller and Trumbore, 2015).

2.2.2 Calculation of solar irradiance: A hemisphere viewshed established in determination of sunshine existence provides a sky view factor (SVF), which indicates the amount of visible sky from an observation point, and the SVF is utilized to calculate solar irradiance of a point of roofs and façades (Zahn, 2015). The virtualcitySOLAR adopts the transition model for direct irradiance and the Standard Overcast Sky (SOC) model for diffuse irradiance according to the algorithm proposed by Fu and Rich (Fu and Rich, 1999). The climate data of the NASA Atmospheric Science Data Centre (ASDC) and the NASA Surface meteorology and Solar Energy (SSE) are utilized to determine parameters of the sky model.

2.3 European Institute for Energy Research (Wieland et al., 2015), (Murshed et al., 2018)

The European Institute for Energy Research (EIFER), Germany developed a piece of software to estimate solar irradiance of building roofs and façades. The software was applied to compute solar irradiance in the city of Karlsruhe in Germany.

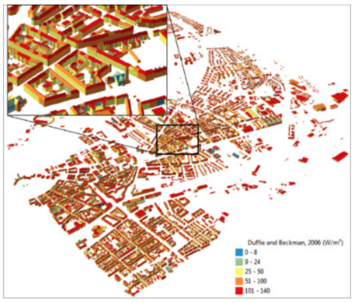


Figure 4. Example of solar irradiance map estimated by the EIFER software (Murshed et al., 2018)

2.3.1 Determination of sunshine existence: At the first in determination of sunshine existence by the EIFER software, from each surface point to calculate solar irradiance, a line is created towards a point of the hemisphere. If the line intersects with another object (e.g., surface of the same building, or another building) the surface point is considered as shaded. If the line is not intersected with another object, the corresponding surface point is considered as not shaded. This process is done for each surface point for every hemisphere direction separately.

2.3.2 Calculation of solar irradiance: The EIFER software adopts the algorithm by Šúri and Hofierka (Šúri and Hofierka, 2004) and the algorithm by Duffie and Beckman (Duffie and Beckman, 2006) to calculate solar irradiance. In the former, only shadowing of the beam component is taken into account, and not of the diffuse irradiance, while the latter utilizes an anisotropic sky model known as the Hay-Davies-Klucher-Reindl sky model to take into account circumsolar diffuse irradiance and horizon-brightening. The Meteonorm software and the Worldwide irradiance data are utilized to determine parameters of the sky model.

3. Outline of our algorithm to estimate solar irradiance of urban buildings

Before presenting the outline of our newly developed algorithm to estimate solar irradiance of urban buildings, we give you a brief outline of the development of a system to estimate PV potential of urban buildings using a 3D city model.

3.1 Requirements to a new system

Requirements to a new system to estimate PV potential of urban buildings using a 3D city model are as follows:

1) A system should be able to estimate PV potential provided by solar panels mounted on not only roofs but also façades of urban buildings in Japanese cities.
2) A system should utilize both LOD1 and LOD2 building data provided by the Project PLATEAU.
3) A system should be able to estimate PV potential with enough details and accuracy within the permissible computation time.
4) A system is available to utilize any dataset open to the public for satisfying the above-mentioned requirements.

3.2 Process flow of our system

Our system has the following process sequence as same as most of existing systems:

1) Creating tree-structured data for the succeeding process
2) Estimating solar irradiance distributions
3) Estimating PV potential

Figure 5 shows the process flow of the developed system.

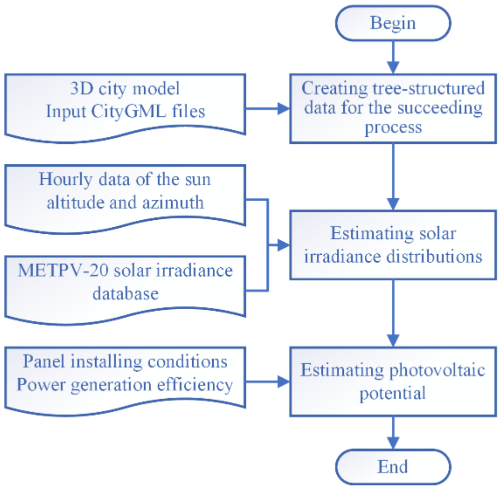


Figure 5. Process flow of the developed system

3.2.1 Creating tree-structured data for the succeeding process: The first step of the processing sequence is the pre-processing step to prepare for the main processing. After loading CityGML files, the system extracts a normal vector, an azimuth, and an elevation of each roof and each façade of a building from its geometry. Additionally, the tree structure consisting of Building – Surface – Polygon – Vertex is constructed for the next main processing.

3.2.2 Estimating solar irradiance distributions:

1) The system establishes an equally spaced grid of points on each roof and each façade where solar irradiance will be calculated.
2) The system creates a projection image viewed by the sun every hour using every hour data of the sun altitude and azimuth provided at the web site of the National Astronomical Observatory of Japan (NAOJ, 2024).
   Since the image indicates sunshine region on each roof and each façade, the system easily determines whether a grid point on a surface has sunshine or not by using the image.
   See Section **3.3.1.** for detailed algorithm.
3) The system adopts a modified Perez sky model for calculation of a diffuse component of inclined surface irradiance. Hourly parameters of the modified Perez sky model are determined by using a solar irradiance database provided by the Meteorological Test data for Photovoltaic system (METPV-20) of the New Energy and Industrial Technology Development Organization (NEDO) of Japan, (NEDO, 2024).
   See Section **3.3.2.** for detailed algorithm.
4) Hourly solar irradiance of a grid point on a roof or a façade is calculated based on whether the point has sunshine or not. If a grid point has sunshine, the point has direct irradiance, isotropic background irradiance, circumsolar irradiance, and horizon brightness irradiance. Meanwhile, a grid point without sunshine has isotropic background irradiance and horizon brightness irradiance.
5) Hourly solar irradiance of a grid point is summed up with respect to given time slot. Usually, monthly solar irradiance or yearly solar irradiance is calculated.

3.2.3 Estimating PV potential:

1) At first the system establishes an equally spaced grid of pixels on each roof and each façade. The interval of pixels is a unit of determination of an arrangement of solar panels mounted on the surface, and that is usually given to be much

small than that of grid points for solar irradiance calculation. For instance, we estimated solar irradiance at intervals of 0.2 m by 0.2 m on a surface in an experiment as described in the next chapter, and we determined an arrangement of solar panels at intervals of 0.02 m by 0.02 m.

2) The system selects excluding pixels on each roof and each façade according to a given clearance by using mathematical morphological operations. Providing width and height of a solar panel arranges solar panels on allowed pixels based on a dedicated algorithm.
3) Since each solar panel has several grid points with solar irradiance, the system calculates solar irradiance of each solar panel by averaging solar irradiance of grid points belonging to the solar panel.
4) If calculated solar irradiance of a solar panel is less than a given minimum solar irradiance, the solar panel will be not installed. Moreover, if the number of solar panels of a roof or a façade is less than a given minimum number of solar panels of a surface, no solar panels are installed on the surface.
5) Solar irradiance of a solar panel is converted to electricity output by using given power generation efficiency.
6) Electricity output of solar panels mounted on roofs and façades of a building is summed up with respect to the building.

3.3 Algorithm to estimate solar irradiance

3.3.1 Determination of hourly sunshine region on each roof and each façade: In a highly obstructed urban area, determination of sunshine regions on each roof and each façade is important for ensuring the accuracy of the solar irradiance estimation. On the other hand, determination of sunshine regions in urban area with densely distributed building is a highly time-consuming task.

Existing systems using a hemispherical viewsheds which is the angular distribution of sky obstruction adopt the idea that “whether we can see the sun or not” indicates “whether we have sunshine or not”. On the other hand, our system adopts the idea that “whether the sun can see us or not” indicates “whether we have sunshine or not” from the point of view of computation time. The former utilizes such a fisheye lens image viewed from a point on the earth as Figure 6 shows, while the latter utilizes hourly projection images viewed from the sun as Figure 7 shows. Figure 7 shows hourly projection images of the Yokohama experiment district, in Japan from 07:00 through 16:00 of January 1 as clockwise from the top right. Each building surface in Figure 7 is coloured according to its ID.

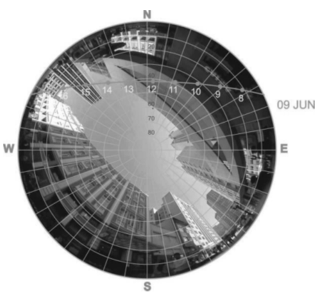


Figure 6. Fisheye image viewed from a point on the earth (Minella et al., 2011)

To know whether the sun can see us or not, our system utilizes projection images viewed by the sun. Using computer graphics (CG) techniques such as the depth buffer (Z-buffer) algorithm which does not examine intersection of the sun ray can provide projection images viewed by the sun much rapidly. In determination of sunshine of many grid points of roofs or façades, the utilization of a projection image from the sun brings less computation time with the same details and accuracy of determination of sunshine as the utilization of a hemispherical viewshed or ray tracing.

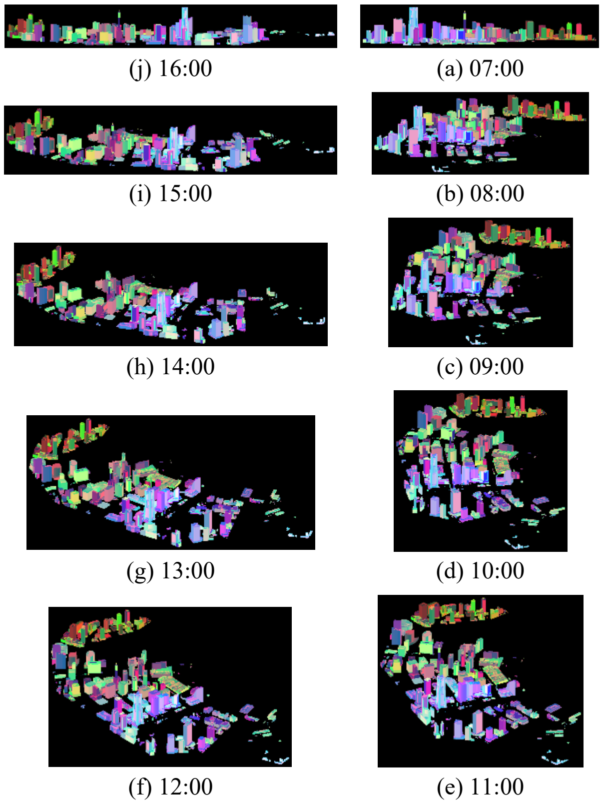


Figure 7. Hourly projection images of January 1 as clockwise from the top right

The utilization of the images from the sun makes the system estimate solar irradiance distribution more densely in permissible time, and we are able to investigate various arrangements of solar panels.

3.3.2 Calculation of hourly solar irradiance of a point on an inclined plane: We adopt the Perez sky model (Perez et al., 1987) as a basic sky model for calculation of hourly solar irradiance of a point on an inclined plane. However, since coefficients of the original Perez sky model were obtained from meteorological observation data of North America and Europe, we are afraid that estimation results of solar irradiance in Japan would not be sufficiently accurate if we use the original Perez sky model. Accordingly, we decided to modify the original Perez model and utilize Japanese solar radiance database in order to obtain parameters of the modified model.

Our system calculates hourly solar irradiance $I_{\alpha\beta}$ of a point on an inclined plane of azimuth α and elevation β by using the following equations:

$$I_{\alpha\beta} = (\cos i) I_{\mathrm{b}} + \left(\frac{1+\cos\beta}{2}\right) I_{\mathrm{ss}} + \left(\frac{\max(0, \cos i)}{\max(\cos 85°, \cos Z)}\right) I_{\mathrm{sb}} + (\sin\beta) I_{\mathrm{sr}}$$

https://doi.org/10.5194/isprs-annals-X-4-W4-2024-115-2024 |

where i is the incident angle of the sun to the plane, Z is the solar zenith angle, and I_b is the direct irradiance of a horizontal plane. The first term $(\cos i) I_b$ is the direct irradiance of an inclined plane, and the rest terms represent the diffuse irradiance of an inclined plane by the modified Perez anisotropic sky model.

$\left(\frac{1+\cos\beta}{2}\right) I_{ss}$, $\left(\frac{\max(0,\cos i)}{\max(\cos 85°, \cos Z)}\right) I_{sb}$, $(\sin\beta) I_{sr}$ are isotropic background irradiance, circumsolar irradiance, and horizon brightness irradiance, respectively.

The system determines the hourly varying parameters I_b, I_{ss}, I_{sb}, I_{sr} by using a solar irradiance database provided by the METPV-20 (NEDO, 2024) of the NEDO. The METPV-20 has three kinds of yearly datasets of every hour solar irradiance at 835 points in Japan. The minimum, maximum, and average yearly datasets were constructed by choosing hourly solar irradiance from 2010 to 2018. A dataset consists of direct and diffuse components of solar irradiance of a horizontal plane, and total of solar irradiance of an inclined plane.

The system determines the hourly varying parameters I_b, I_{ss}, I_{sb}, I_{sr} of the modified Perez sky model by using the METPV-20 solar irradiance database.

4. Experiment

We conducted an experiment to evaluate the developed system by using a 3D city model in one of Japanese large cities.

4.1 Outline of the experiment

The experiment utilized a 3D city model of the Minato Mirai 21 and its surrounding area in Yokohama, Japan. The Minato Mirai 21 is a seaside urban renewal area, and is the central business district of Yokohama now. It has a lot of large high-rises, including the Landmark Tower, which is the third-tallest building in Japan, standing 296.3 m high. Figure 8 and Figure 9 show the experiment area of 2.27 km^2 which has 390 LOD2 buildings. The 2D map and the aerial image of the experiment area in Figure 9 were obtained at the GSI (Geospatial Information Authority of Japan) web map service (GSI, 2024), and 3D view images in Chapter 4 such as Figure 9 were obtained at the PLATEAU view (MLIT, 2024).

Figure 8. 2D map and aerial image of the experiment area

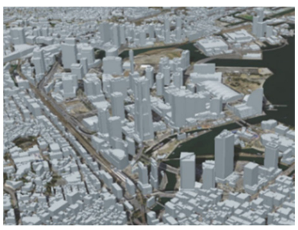


Figure 9. 3D view image of the experiment area

4.2 Results and discussion

We established a grid of points at intervals of 0.2 m by 0.2 m on each roof and each façade for calculation of solar irradiance, while we utilized a grid of pixels at intervals of 0.02 m by 0.02 m on each roof and each façade for estimation of PV potential.

4.2.1 Outline of the calculation results: Table 1 shows the characteristics of roofs and façades of 390 LOD2 buildings in the experiment. The numbers of grid points shown in Table 1 are those of grid points to be calculated solar irradiance. Solar irradiance shown in Table 1 is calculated in the experiment.

Table 1. Characteristics of roofs and façades of 390 LOD2 buildings in the experiment

	Roofs	Façades	Base
CityGML thematic class	RoofSurface	WallSurface	GroundSurface
Polygons	22,985	25,679	460
Area (m^2)	625,810	2,464,363	609,076
Grid points	16,055,975	62,255,225	N/A
Solar irradiance (kWh)	724.94×10^6	1563.29×10^6	N/A
Solar irradiance density (kWh / m^2)	1158.40	634.36	N/A

Calculating hourly solar irradiance of each grid point for a year, which is the most time-consuming task in the system processing, took nearly five hours with use of a CPU core of 3.6 GHz. Calculation of solar irradiance is executed hour by hour, and calculations of hourly solar irradiance are independent each other. Accordingly, if we utilize six CPU cores for calculation of hourly solar radiation, we will be able to obtain yearly solar irradiance in at most an hour.

Table 2 shows yearly solar irradiance of a horizontal plane and vertical planes of Yokohama in the average dataset of the METPV-20 solar irradiance database. These values were utilized as reference data in the evaluation of estimation results by the developed system. Figure 10 shows the colour scale utilized for representing calculated solar irradiance distribution in the experiment. “N”, “W”, “E”, and “S” in Figure 10 mean solar irradiance of a north-facing vertical plane, a west-facing one, an east-facing one, and a south-facing one, while “Hor.” in Figure 10 means solar irradiance of a horizontal plane.

Table 2. Average yearly solar irradiance of horizontal plane and vertical planes

Plane	Azimuth	kWh / m^2
Horizontal plane		1412.7
Vertical plane	North	413.0
	Northeast	545.6
	East	820.5
	Southeast	1036.6
	South	1108.1
	Southwest	1027.3
	West	806.7
	Northwest	535.2

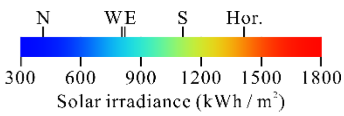
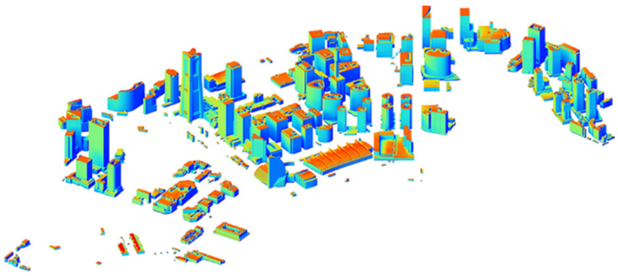


Figure 10. Colour scale for representing calculated solar irradiance distribution

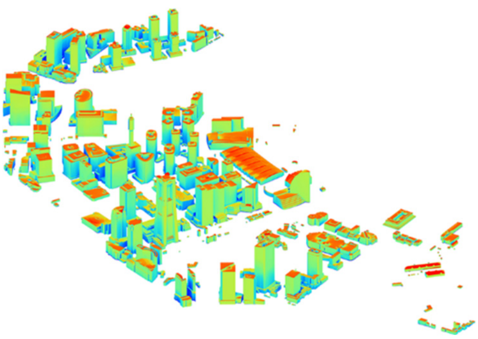
4.2.2 Evaluation of the overall experiment area: At first, we qualitatively evaluated the function of the system to estimate solar irradiance distributions on roofs and façades by visual inspection of colour projection images of solar irradiance. We created colour projection images all over the experiment area viewed from various azimuths and dips. The visual inspection was conducted from the following points of view:

i) Whether is there no significant difference between estimated solar irradiance on vertical planes and the reference METPV-20 solar irradiance database?
ii) Whether does estimated solar irradiance on a vertical plane vary according to its azimuth?
iii) If a roof or a façade of interest has a shade of its surrounding building, whether is estimated solar irradiance distribution properly affected by the shading?

Figure 11 shows examples of colour projection images of solar irradiance utilized for the visual inspection. Figure 11 (a) is a colour projection image viewed from the east with the dip of 30°, and Figure 11 (b) is one from the south with the dip of 30°.



(a) Viewed from the east with the dip of 30°



(b) Viewed from the south with the dip of 30°

Figure 11. Colour projection images of solar irradiance utilized for visual inspection

The visual inspection of colour projection images of solar irradiance indicates that the system would be able to estimate solar irradiance distributions on both roofs and façades properly.

4.2.3 Evaluation of an individual building: We selected 14 buildings in various shapes in the experiment area to evaluate the validity the developed system. The experiment results of an individual building were investigated from the following points of view of qualitative and quantitative evaluation:

1) Qualitative evaluation
   Qualitative evaluation of an individual building was conducted by visual inspection of colour surface images of solar irradiance distribution. The visual inspection was conducted from the following points of view:
   i) Whether does estimated solar irradiance on a vertical plane vary according to its azimuth?
   ii) If a roof or a façade of interest has a shade of its surrounding building, whether is estimated solar irradiance distribution properly affected by the shading?
2) Quantitative evaluation
   As for quantitative evaluation of an individual building, we compared estimated solar irradiance with the METPV-20 solar irradiance database, because there is no observation station to measure solar irradiance in the experiment area. Since solar irradiance in the METPV-20 solar irradiance database is solar irradiance on no shading plane, we compared the maximum solar irradiance of grid points on a roof or a façade with the solar irradiance in the METPV-20 solar irradiance database which is a reference. The quantitative evaluation was conducted mainly with respect to façades and inclined roofs.

The experiment results of three buildings, the Yokohama City Hall Building, the InterContinental Yokohama Grand, and the Fuji Xerox R&D Square are presented in the paper.

[1] Yokohama City Hall Building
Figure 12 shows a 3D view image of the Yokohama City Hall Building and its surrounding. Figure 13 shows colour projection images of calculated solar irradiance of the building. Table 3 shows the calculated solar irradiance of four façades of the building.

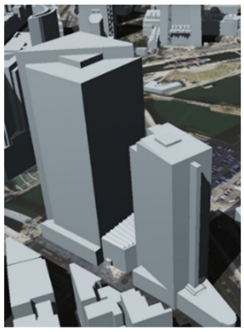
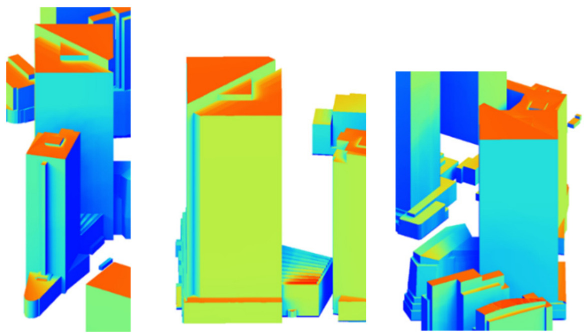


Figure 12. 3D view image of the Yokohama City Hall Building and its surrounding

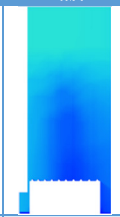
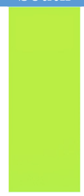


(a) From the east (b) From the south (c) From the west

Figure 13. Colour projection images of solar irradiance of the Yokohama City Hall Building

https://doi.org/10.5194/isprs-annals-X-4-W4-2024-115-2024 | © Author(s) 2024. CC BY 4.0 License.

Table 3. Solar irradiance of the façades of the Yokohama City Hall Building

Façade	East	South	West	North
Solar irradiance distribution				
Calculated	817 kWh/m^2	1066 kWh/m^2	806 kWh/m^2	387 kWh/m^2
Reference	821 kWh/m^2	1108 kWh/m^2	807 kWh/m^2	413 kWh/m^2
Error	-0.4%	-3.8%	-0.1%	-6.4%

We judged that the distribution of solar irradiance of the east façade is affected by shading of a building next to the east. The distribution of solar irradiance of the west façade would be affected by shading of lower buildings next to the west as well. The results shown in Figure 13 and Table 3 indicate that the developed system would be able to take shading of the surrounding building into account properly in estimation of solar irradiance distribution.

Calculated solar irradiance of three polygons of the horizontal roof of the Yokohama City Hall Building are 1374.7 kWh / m^2, 1370.0 kWh / m^2, and 1372.4 kWh / m^2. Ratios of those to the reference of 1412.7 kWh / m^2 are 97.3%, 97.0%, and 97.1%, respectively. The numerical results including those of façades as shown in Table 3 demonstrate that the system would be able to estimate solar irradiance with sufficient accuracy.

[2] The InterContinental Yokohama Grand

Figure 14 shows a 3D view image of the InterContinental Yokohama Grand. Calculated results of the building were principally utilized for the investigation of inclined surfaces of various inclination angles. Figure 15 shows a colour projection image of calculated solar irradiance of the building. Calculated solar irradiance of inclined surfaces of the building are plotted against an inclination angle of a surface in Figure 16.

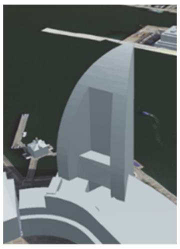


Figure 14. 3D view image of the InterContinental Yokohama Grand

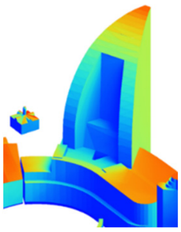


Figure 15. Colour projection image of solar irradiance of the InterContinental Yokohama Grand viewed from the west

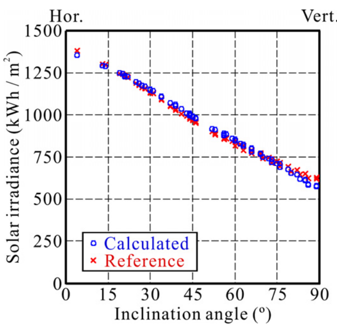


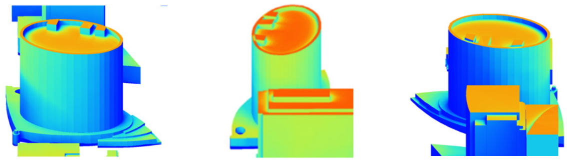
Figure 16. Calculated solar irradiance of inclined surfaces of the InterContinental Yokohama Grand.

The root mean squares (RMS) of 82 error rates of solar irradiance of inclined surfaces shown in Figure 16 is 2.6%, and the maximum error rate is 8.3%. The calculation results demonstrate that the system would be able to estimate solar irradiance of inclined surfaces with satisfactory accuracy.

[3] Fuji Xerox R&D Square

Figure 17 shows a 3D view image of the Fuji Xerox R&D Square of an elliptic cylinder. Calculated results of the building were principally utilized for the investigation of vertical surfaces of various azimuths. Figure 18 shows colour projection images of calculated solar irradiance of the building. Calculated solar irradiance of vertical surfaces of the building are plotted against an azimuth of a surface in Figure 19.

Figure 17. 3D view image of the Fuji Xerox R&D Square



(a) From the east (b) From the south (c) From the west

Figure 18. Colour projection images of solar irradiance of the Fuji Xerox R&D Square

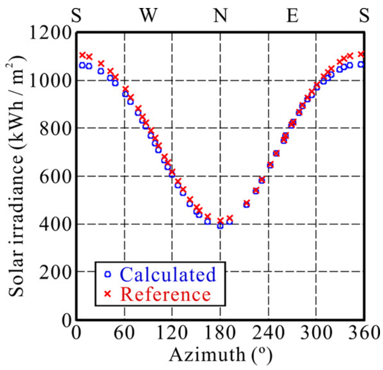


Figure 19. Calculated solar irradiance of vertical surfaces of the Fuji Xerox R&D Square

The root mean squares (RMS) of 45 error rates of solar irradiance of vertical surfaces shown in Figure 19 is 2.6%, and the maximum error rate is 4.9%. The calculation results indicate that the system would be able to estimate solar irradiance of vertical surfaces of various azimuths enough accurately.

Moreover Figure 18 (a) and (b) indicate that shading of a building next to the south would affect the solar irradiance distribution of the lower part of southern vertical surfaces of the building.

5. Conclusion

We have developed an algorithm to estimate solar irradiance of urban buildings for PV potential estimation system using a 3D city model. The experiment results demonstrate that the algorithm would be able to estimate solar irradiance of not only roofs and but also façades of urban buildings using 3D city model in Japan accurately enough.

The most significant feature of our newly developed algorithm is that the system adopts the idea that "whether the sun can see us or not" indicates "whether we have sunshine or not" for calculation of hourly solar irradiance of a grid point. In estimation of solar irradiance distributions on roofs and façades, utilization of projection images viewed from the sun created by using CG techniques such as the depth buffer (Z-buffer) algorithm makes our system much less computation time than most of existing systems using a hemispherical viewsheds or ray tracing.

As for calculation of hourly solar irradiance of a point on an inclined plane, we adopt a modified Perez sky model and utilize Japanese solar irradiance database to obtain parameters of the model. As a result, our system can estimate solar irradiance of a point on an inclined plane enough accurately in Japan. We consider that our algorithm would be able to estimate solar irradiance with acceptable accuracy by using sky model suitable to any area in the world.

The rapid calculation of hourly solar irradiance of a grid point by the algorithm enables a PV potential estimation system to handle more flexible arrangement of solar panels with providing panel installing conditions such as width and height of a solar panel, and clearance around solar panels. Consequently, PV potential estimated by the system would become more realistic.

References

Alam, N., Coors, V., Zlatanova, S. 2013. Detecting shadow for direct radiation using CityGML models for photovoltaic potentiality analysis, *Urban and Regional Data Management*, 191-210, Taylor & Francis Group, London, UK.

Chaturvedi, K., Willenborg, B., Sindram, M., Kolbe, T. H., 2017. Solar Potential Analysis and Integration of the Time-Dependent Simulation Results for Semantic 3d City Models Using Dynamizers, *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*, IV-4/W5, 25-32.

Duffie, J. A., Beckman, W. A., 2006. *Solar engineering of thermal processes, 3rd Edition*, John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

Fu, P., Rich, P. M., 1999. Design and implementation of the Solar Analyst: an ArcView extension for modeling solar radiation at landscape scales. *Proceedings of the Nineteenth Annual ESRI User Conference*, 1-31.

Geospatial Information Authority of Japan (GSI), 2024. https://maps.gsi.go.jp/ (February 29, 2024).

Hay, J. E., 1976. A revised method for determining the direct and diffuse components of the total short-wave radiation, *Atmosphere*, 14(4), 278-287.

Hay, J. E., McKay, D. C., 1985. Estimating solar irradiance on inclined surfaces: a review and assessment of methodologies, *International Journal of Solar Energy*, 3(4-5), 203-240.

INSEL, 2024. A Simulation System for Renewable Energy Supply Systems, https://www.insel.eu/en/home_en.html (February 29, 2024).

Minella, F., Rossi, F. A., Krüger, E., 2011. Analysis of the daytime effect of the sky view factor on the microclimate and on thermal comfort levels in pedestrian streets of Curitiba, *Ambiente Construído*, 11(1), 123-143.

Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), 2024. https://www.mlit.go.jp/plateau (February 29, 2024).

Möller, T., Trumbore, B., 2015. Fast, minimum storage ray/triangle intersection, *SIGGRAPH '05: ACM SIGGRAPH 2005 Courses*, 7-es.

Murshed, S. M., Simons, A., Lindsay, A., Picard, S., 2018. Evaluation of Two Solar Radiation Algorithms on 3D City Models for Calculating Photovoltaic Potential, *Proceedings of the 4th International Conference on Geographical Information Systems Theory, Applications and Management - GISTAM*, 296-303.

National Astronomical Observatory of Japan (NAOJ), Altitude / Azimuth of Solar System Bodies, https://eco.mtk.nao.ac.jp/cgi-bin/koyomi/cande/horizontal_en.cgi (February 29, 2024).

New Energy and Industrial Technology Development Organization (NEDO), NEDO Solar radiation database browsing system, https://appww2.infoc.nedo.go.jp/appww/index.html (February 29, 2024).

Nouvel, R., Brassel, K.-H., Bruse, M., Duminil, E., Coors, V., Eicker, U., Robinson, D., 2015. SimStadt, a new workflow-driven urban energy simulation platform for CityGML city models, *Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale*, 889-894.

Perez, R., Seals, R., Ineichen, P., Stewart, R., Menicucci, D., 1987. A new simplified version of the Perez diffuse irradiance model for tilted surfaces, *Solar Energy*, 39(3), 221-231.

PVGIS, 2024. Photovoltaic Geographical Information System, https://joint-research-centre.ec.europa.eu/pvgis-photovoltaic-geographical-information-system_en (February 29, 2024).

Robinson, D., Stone, A., 2005. A simplified radiosity algorithm for general urban radiation exchange, *Building Services Engineering Research and Technology*, 26(4), 271-284,.

Rodríguez, L. R., Duminil, E., Ramos, J. S., Eicker, U. , 2017. Assessment of the photovoltaic potential at urban level based on 3D city models: A case study and new methodological approach, *Solar Energy*, 146, 264-275.

SimStadt, 2024a. http://simstadt.hft-stuttgart.de/ (February 29, 2024).

Šúri, M., Hofierka, J., A new GIS-based solar radiation model and its application to photovoltaic assessments, *Transactions in GIS*, 8(2), 175-190.

virtualcitysystems GmbH, 2024. https://www.pf.bgu.tum.de/pfgk18/img/pfgk18_virtualcitySYSTEMS-Exponate.pdf (February 29, 2024).

Wieland, M., Nichersu, A., Murshed, S. M., Wendel, J., 2015. Computing Solar Radiation on CityGML Building Data, *AGILE2015: 18th AGILE International Conference on Geographical Information System*.

Willenborg, B., Sindram, M., Kolbe, T. H., 2018. Applications of 3D City Models for a Better Understanding of the Built Environment, *Trends in Spatial Analysis and Modelling*, 167-191, Springer International Publishing AG, Cham, Switzerland.

Zahn, W., 2015. Sonneneinstrahlungsanalyse auf und Informationsanreicherung von großen 3D-Stadtmodellen im CityGML-Schema, *Masterarbeit*, Technische Universität München.