Estimation of Photovoltaic Potential of Urban Buildings Considering a Solar Panel Arrangement Using a 3D City Model

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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 have developed 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 method to estimate PV potential of urban buildings considering an arrangement of solar panels using dense solar irradiance distribution on a building surface. The rapid estimation of dense solar irradiance distribution on a building surface enables the system to handle more flexible arrangement of solar panels with providing width and height of a solar panel, and clearance around solar panels. Considering some restrictions such as minimum solar irradiance of a solar panel makes PV potential estimated by the system become more realistic. The paper reports experiments conducted in seven urban districts in Japan to investigate the flexibility of the method by using various settings of panel installing conditions. Experiment results indicate that our developed method can estimate PV potential flexibly considering an arrangement of solar panels corresponding to various settings of panel installing conditions such as size of a solar panel.

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 method to estimate PV potential considering an arrangement of solar panels using dense solar irradiance distribution on a building surface. Moreover the paper reports experiments conducted in seven urban districts in Japan to investigate the flexibility of the method by using various settings of panel installing conditions.

2. Existing systems

There is no system to estimate PV potential of both building roofs and façades using a 3D city model in Japan. Meanwhile there are several systems developed in Europe which have capability to estimate solar irradiance of urban building surface by using CityGML data. These systems which might have capability to estimate PV potential at city districts level are briefly reviewed.

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Review is also conducted from the point of view of the algorithm for determination of sunshine existence of a surface point to calculate solar irradiance. The reason is that we acknowledge that flexible estimation of PV potential considering an arrangement of solar panels requires dense solar irradiance distribution on building surface. Determination of sunshine existence of a surface point is a key issue to calculate solar irradiance, because it is the most time consuming process.

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).

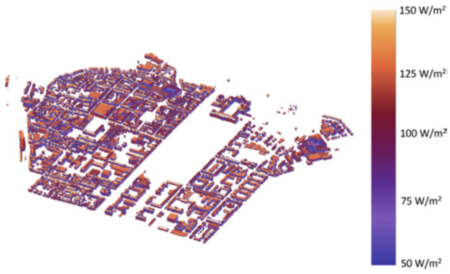


Figure 2. Example of solar irradiance map estimated by the SimStadt (Nouvel et al., 2015)

The SimStadt has capability to estimate PV potential of buildings. However, since the SimStadt does not require width and height of a solar panel (2024), estimation of PV potential considering an arrangement of solar panels is judged unable in the SimStadt. As for estimation of PV potential SimStadt (2024) announces "This simulation is only a rough estimate. It might return correct orders of magnitude, provided the 3D-model, weather, irradiance and input parameters are correct."

Moreover determination of sunshine existence for estimation of solar irradiance of building surfaces 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).

We consider that the SimStadt would be difficult to conduct flexible estimation of PV potential considering an arrangement of solar panels based on dense solar irradiance distribution, because ray tracing requires much more time than our algorithm using projection images viewed from the sun.

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).

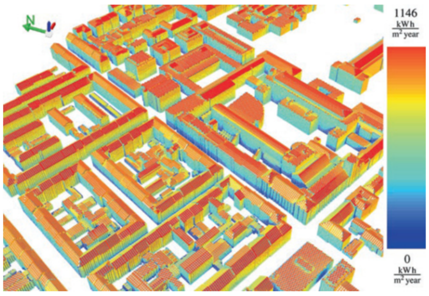


Figure 3. Example of solar irradiance map estimated by the virtualcitySOLAR (Willenborg et al., 2018)

The virtualcitySOLAR determines sunshine existence for estimation of solar irradiance of building surfaces as follows: At the first 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).

No description about a way to estimate PV potential of buildings in the virtualcitySOLAR has been found. Meanwhile we consider that the virtualcitySOLAR's algorithm to determine sunshine existence would requires much more time than our algorithm using projection images viewed from the sun. Accordingly the virtualcitySOLAR would be difficult to obtain dense solar irradiance distribution on a building surface, and as a result the virtualcitySOLAR would be unable to conduct flexible estimation of PV potential considering an arrangement of solar panels.

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.

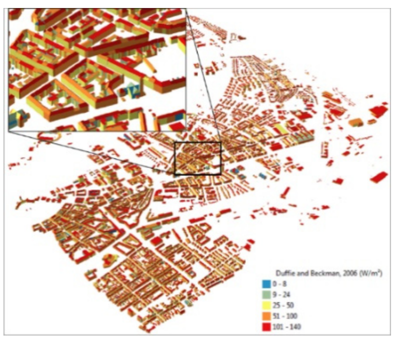


Figure 4. Example of solar irradiance map estimated by the EIFER software (Murshed et al., 2018)

The EIFER software determines sunshine existence for estimation of solar irradiance of building surfaces as follows: At the first 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.

No description about a way to estimate PV potential of buildings in the EIFER software has been found. Meanwhile we consider that the EIFER software's algorithm to determine sunshine existence would requires much more time than our algorithm using projection images viewed from the sun. Accordingly the EIFER software would be difficult to obtain dense solar irradiance distribution on a building surface, and as a result the EIFER software would be unable to conduct flexible estimation of PV potential considering an arrangement of solar panels.

3. Outline of our system to estimate PV potential at city districts level using a 3D city model

Before presenting our new method to estimate PV potential of urban buildings considering an arrangement of solar panels, we give you a brief outline of the development of our system to estimate PV potential at city districts level using a 3D city model.

3.1 Requirements to a new system

Requirements to a new system to estimate PV potential at city districts level using 3D city models 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.

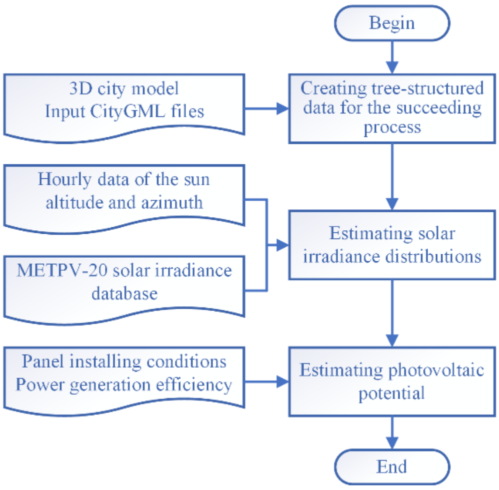


Figure 5. Process flow of the developed system

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.** 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).
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 with calculated solar irradiance.
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 calculated 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 Determination of hourly sunshine region

Determination of hourly sunshine region on each roof and each façade is one of key issues in our developed system. 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 Yokohama district 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.

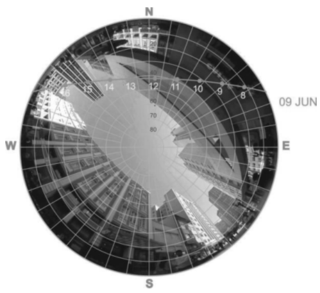


Figure 6. Fisheye image viewed from a point on the earth (Minella et al., 2011)

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.

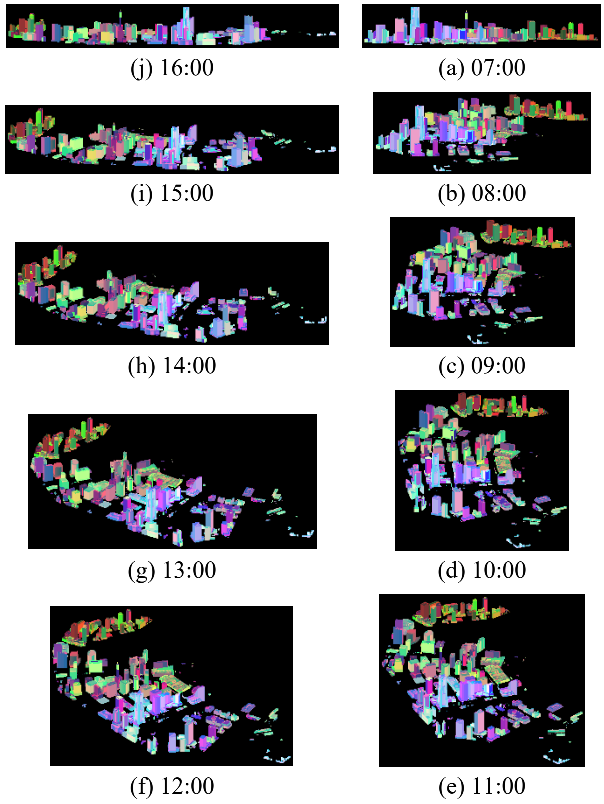
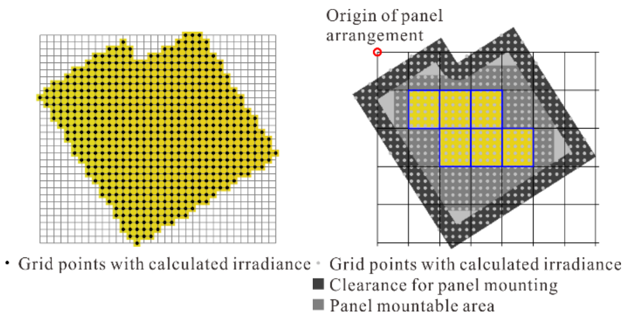


Figure 7. Hourly projection images of January 1 as clockwise from the top right

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.

3.4 Arrangement of solar panels according to panel installing conditions

3.4.1 Basic idea to arrange solar panels: The system can handle arrangement of solar panels more flexibly against arrangement of grid points where solar irradiance is estimated. Using mathematical morphological operations enables providing width and height of a solar panel, and clearance around solar panels to determine an arrangement of solar panels. For instance, even if we estimate solar irradiance at intervals of 0.2 m by 0.2 m on a surface, we can determine an arrangement of solar panels at intervals of 0.02 m by 0.02 m on a surface. Figure 8 shows an example of determining an arrangement of solar panels according to a panel installing condition.



(a) Grid points with calculated solar irradiance (b) Solar panel arrangement with clearance

Figure 8. Arrangement of solar panels according to a panel installing condition

3.4.2 Panel installing conditions to be considered: Our system determines an arrangement of solar panels on each surface according to a set of the following parameters:

i) arrangement type of solar panels
ii) lower margin of a surface
iii) clearance around solar panels on a surface
iv) width and height of a solar panel
v) minimum solar irradiance of a solar panel
vi) minimum number of solar panels on a surface

Sets of the above parameters can be given for roofs and façades respectively.

A. Arrangement type of solar panels

Our method can handle four types to arrange solar panels as Figure 9 shows. Difference between Type Grating-I and Type Grating-II is difference of the origin of a panel arrangement. The origin of Type Grating-I is defined by a region of a surface excluding clearance, while that of Type Grating-II is defined by a panel mountable area. Type Slip-V and Type Slip-H permit discrepancy among columns and discrepancy among rows, respectively.

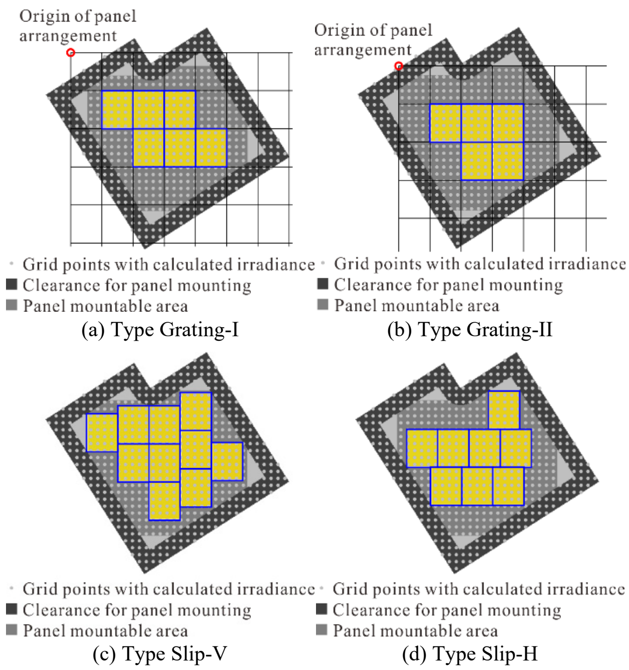


Figure 9. Arrangement type of solar panels

B. Width and height of a solar panel

Size of a solar panel may make an impact on PV potential of a small surface. Figure 10 shows panel arrangements of two sizes of a solar panel. One is the arrangement of solar panels with 0.9 m wide and 1.6 m high, that other is that of solar panels with 1.6 m wide and 0.9 m high. Difference of size makes difference of panel mountable area, and finally difference of number of mountable solar panels.

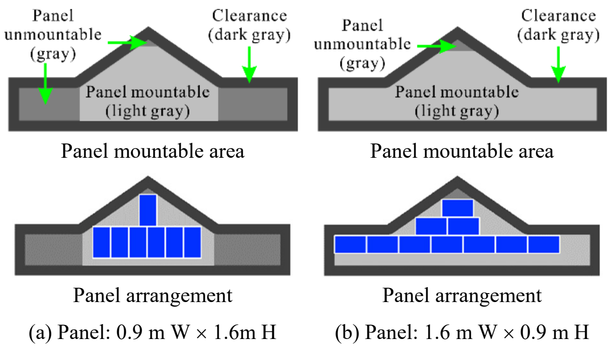


Figure 10. Panel arrangement of different size of a solar panel

C. Minimum solar irradiance of a solar panel

Since sunshine on a façade is apt to be more influenced by shading of surrounding buildings than sunshine on a roof in urban area, solar irradiance on a façade varies largely. Considering economics in installing solar panel, it is not desirable that placing solar panels all over a façade. The system has a function to select only solar panels with sufficient solar irradiance.

Figure 11 shows two panel arrangements corresponding the minimum solar irradiance of 0 kWh / m^2 and 800 kWh / m^2. Each panel in Figure 11 is colourized according to its solar irradiance. Figure 11 indicates that sunshine on a façade is more influenced by shading of surrounding buildings than sunshine on a roof.

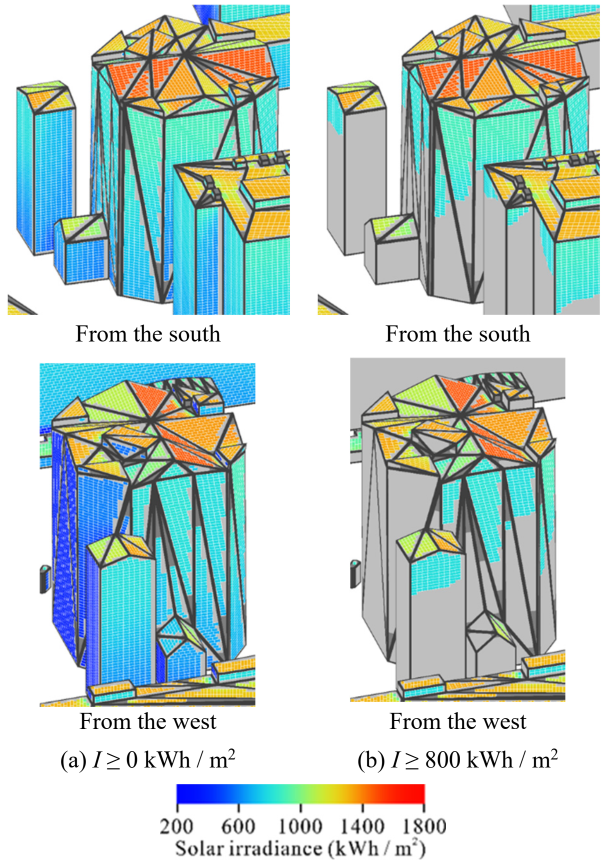


Figure 11. Panel arrangements corresponding minimum solar irradiance

4. Experiment

We conducted an experiment to evaluate impact of panel installing conditions on estimated PV potential.

4.1 Outline of the experiment

In the experiment we estimated PV potential of seven districts: Utsunomiya in Tochigi Prefecture, Ikebukuro, Itabashi, Otemachi-Marunouchi-Yurakucho (OMY), Shibuya, Shinjuku in Tokyo Metropolitan Government, and Yokohama in Kanagawa Prefecture. Table 1 shows numbers of buildings, and areas of roofs and façades per building of the experiment districts. In Utsunomiya and Itabashi smaller buildings are dominant, while in OMY large buildings are much dominant, and in Yokohama, Shinjuku and Shibuya large buildings would be somewhat dominant.

Table 1. Numbers of buildings, and areas of roof and façade per building of the experiment districts

	Number of buildings	Area (m^2) per building	
		Roof	Façade
Tochigi - Utsunomiya	6,721	142	496
Tokyo - Ikebukuro	3,289	204	1,126
Tokyo - Itabashi	4,293	217	579
Tokyo - OMY	234	2,277	13,318
Tokyo - Shibuya	2,342	291	1,752
Tokyo - Shinjuku	3,489	319	1,850
Kanagawa -Yokohama	2,123	500	2,244

Table 2 shows yearly solar irradiance of horizontal and vertical planes of Utsunomiya (36°32.9´ N, 139°52.1´ E), Tokyo (35°41.5´ N, 139°45.0´ E), and Yokohama (35°26.3´ N, 139°39.1´ E) obtained from the METPV-20 of the NEDO.

Table 2. Yearly solar irradiance (kWh / m^2) of horizontal and vertical planes

Plane	Azimuth	Utsunomiya	Tokyo	Yokohama
Horizontal		1381.5	1367.8	1412.7
Vertical	North	425.8	422.3	413.0
	Northeast	554.8	547.6	545.6
	East	840.0	815.9	820.5
	Southeast	1077.1	1032.1	1036.6
	South	1155.6	1101.3	1108.1
	Southwest	1041.6	1016.0	1027.3
	West	798.2	799.3	806.7
	Northwest	531.4	540.0	535.2

Yearly solar irradiance at intervals of 0.2 m by 0.2 m on a surface was estimated in the experiment. Table 3 shows numbers of grid points and computation time with use of a CPU core of 3.6 GHz of the experiment districts. The computation time is not always proportional to a number of grid points. The computation time would depend on features of a district such as density and arrangement of buildings, and size of each building. Our system calculated yearly solar irradiance of 2,090 (Itabashi) to 6,378 (OMY) grid points per second.

Table 3. Number of grid points and computation time of the experiment districts

	# of grid points	Computation time
Tochigi - Utsunomiya	115,648,651	7.60 hour
Tokyo - Ikebukuro	116,718,768	7.22 hour
Tokyo - Itabashi	90,460,040	12.02 hour
Tokyo - OMY	94,907,527	4.13 hour
Tokyo - Shibuya	127,280,268	5.74 hour
Tokyo - Shinjuku	200,695,456	10.73 hour
Kanagawa -Yokohama	151,715,279	14.28 hour

By using the estimated yearly solar irradiance distributions shown in Figure 12 we estimated PV potential for evaluation of the impact of panel installing conditions on estimated PV potential.

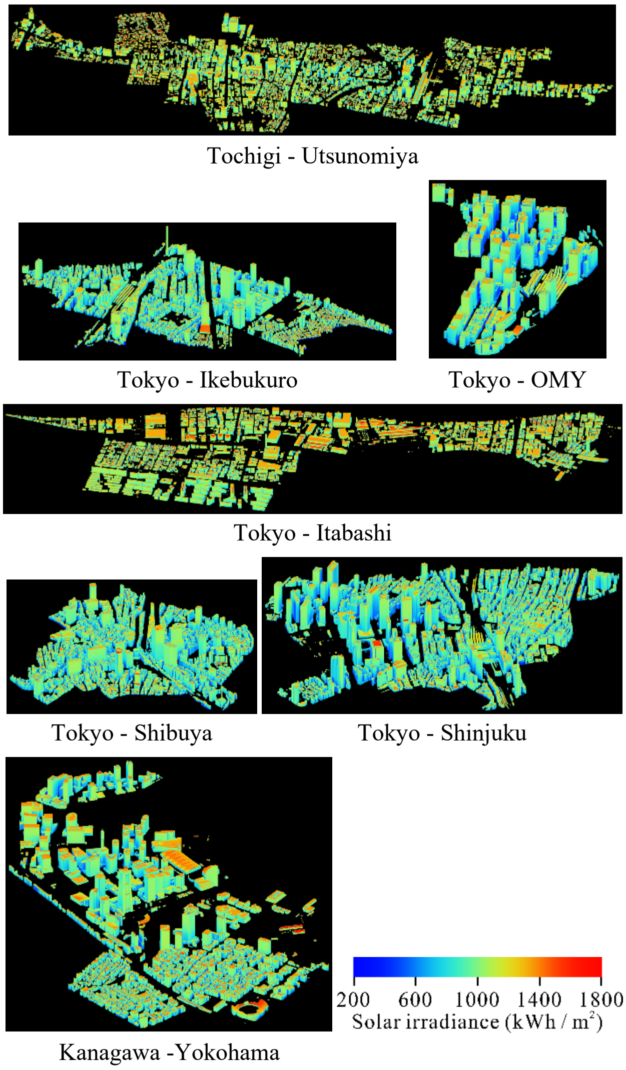


Figure 12. Estimated solar irradiance of the experiment districts

4.2 Impact of panel installing conditions

4.2.1 Arrangement type of solar panels: Table 4 shows ratios of PV potential of the worst arrangement type to the best arrangement type.

Table 4. Ratio of PV potential of the worst arrangement type to the best arrangement type

Panel		Best	Worst	Ratio of worst to best
0.90 m W × 1.60 m H	Roof	Slip-V	Grating-II	82.0% (Shibuya) ~ 91.4% (OMY)
	Façade	Slip-V	Grating-I	95.2% (Itabashi) ~ 99.7% (OMY)
1.60 m W × 0.90 m H	Roof	Slip-H	Grating-I	82.6% (Shibuya) ~ 91.8% (Itabashi)
	Façade	Slip-H	Grating-II	96.9% (Utsunomiya) ~ 99.5% (OMY)
0.82 m W × 0.82 m H	Roof	Slip-V	Grating-II	90.1% (Shibuya) ~ 95.2% (OMY)
	Façade	Slip-V	Grating-I	97.7% (Itabashi) ~ 99.6% (OMY)

The experiment results indicate that PV potential of Type Grating-I and Type Grating-II are nearly equal, while PV potential of Type Slip-V and Type Slip-H are nearly equal. Moreover the results show that Type Slip-V and Type Slip-H are better than Type Grating-I and Type Grating-II. The differences between the best type and the worst type of façades are small and would be able to be neglected.

4.2.2 Lower margin of a surface: Restriction of lower margin H_L means that a solar panel should not be placed below H_L plus the elevation of GroundSurface of a building. Table 5 shows ratios of PV potential of H_L = 3.5 m to no restriction of lower margin as to three sizes of a solar panel. H_L = 3.5 m means that no solar panels will be placed on façades of a ground floor of a building.

Table 5. Ratios of PV potential of lower margin H_L = 3.5 m to no restriction of lower margin

Width	Height	Façade
0.900 m	1.600 m	86.9% (Itabashi) ~ 98.2% (OMY)
1.600 m	0.900 m	81.5% (Itabashi) ~ 97.2% (OMY)
0.820 m	0.820 m	81.4% (Itabashi) ~ 97.2% (OMY)

PV potential estimated considering lower margin restriction decrease much more in small building dominant districts such as Itabashi and Utsunomiya than in large building dominant districts such as OMY and Yokohama. We consider that difference of a size of a façade would affect the results.

4.2.3 Clearance around solar panels on a surface: Table 6 shows ratios of PV potential of clearance 0.5 m to no restriction of clearance in case of solar panels with 0.82 m wide and 0.82 m high.

Table 6. Ratios of PV potential of clearance 0.5 m to no restriction of clearance

Panel	Roof	Façade
0.82 m W 0.82 m H	67.4% (Utsunomiya) ~ 81.9% (OMY)	73.4% (Utsunomiya) ~ 89.7% (OMY)

As similar to lower margin restriction, PV potential estimated considering clearance restriction decrease much more in small building dominant districts such as Itabashi and Utsunomiya than in large building dominant districts such as OMY and Yokohama. Moreover decrease in roofs is larger than in façades. Difference of a size of a surface would affect the results.

4.2.4 Minimum solar irradiance of a solar panel: Table 7 shows ratio of PV potential of minimum solar irradiance 420 kWh / m^2, 540 kWh / m^2, and 800 kWh / m^2 to no restriction of minimum solar irradiance. Solar irradiance 420 kWh / m^2, 540 kWh / m^2, and 800 kWh / m^2 is nearly equal to solar irradiance of vertical planes of the north-facing, the northeast-facing and the northwest-facing, and the east-facing and the west-facing, respectively.

Table 7. Ratios of PV potential of minimum solar irradiance 420 kWh / m^2, 540 kWh / m^2, 800 kWh / m^2 to no restriction of minimum solar irradiance

	Roof	Façade
$I \geq 420$ kWh / m^2	99.7% (Shinjuku) ~ 100.0% (Utsunomiya)	68.6% (Shibuya) ~ 79.6% (Utsunomiya)
$I \geq 540$ kWh / m^2	97.9% (Shinjuku) ~ 99.8% (Utsunomiya)	49.6% (Shibuya) ~ 70.8% (Utsunomiya)
$I \geq 800$ kWh / m^2	85.9% (Shinjuku) ~ 98.9% (Itabashi)	23.2% (Shinjuku) ~ 41.0% (Itabashi)

PV potential estimated considering minimum solar irradiance restriction decrease much more in districts where large building is dominant and density of building is high such as Shinjuku and Shibuya than in small building dominant districts such as Itabashi and Utsunomiya.

Table 7 demonstrates that the minimum solar irradiance restriction has great impact on PV potential of façades, while that has small impact on PV potential of roofs. The reason of the large decrease of PV potential of façades is that sunshine on a façade is apt to be much influenced by shading of surrounding buildings.

Figure 13 shows estimated solar irradiance I, and estimated electricity power P per building in Shinjuku which has the large decrease of PV potential by minimum solar irradiance restriction.

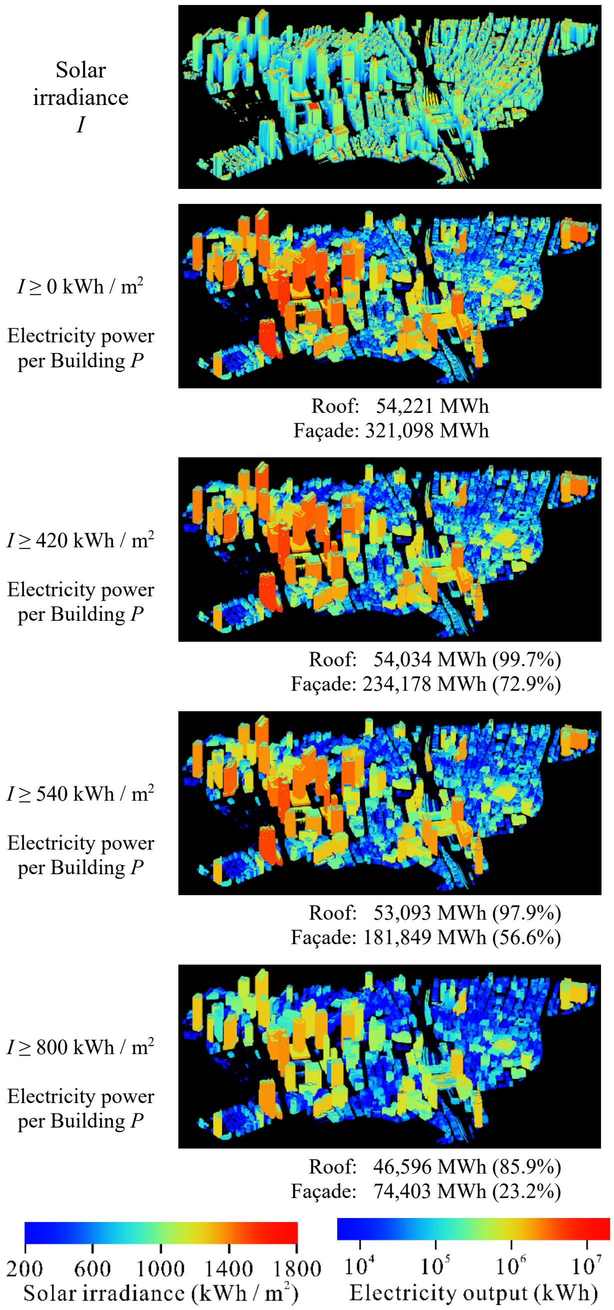


Figure 13. Estimated solar irradiance I, and estimated electricity power P per building in Shinjuku

4.2.5 Minimum number of solar panels on a surface: Table 8 shows ratios of PV potential of minimum number 10 of solar panels to no restriction of minimum number of solar panels.

Table 8. Ratios of PV potential of minimum number 10 of solar panels to no restriction of minimum number of solar panels

Width	Height	Roof	Façade
0.900 m	1.600 m	91.3% (Utsunomiya) ~ 99.0% (OMY)	93.9% (Utsunomiya) ~ 99.5% (OMY)
1.600 m	0.900 m	90.0% (Utsunomiya) ~ 98.9% (OMY)	93.8% (Utsunomiya) ~ 99.5% (OMY)
0.820 m	0.820 m	94.2% (Utsunomiya) ~ 99.5% (OMY)	97.4% (Utsunomiya) ~ 99.8% (OMY)

That a RoofSurface is generally smaller than a WallSurface would affect that decrease of PV potential by the minimum number restriction in roofs is larger than in façades. However Table 8 indicates that the impact of the minimum number restriction on PV potential would be able to be neglected.

5. Conclusion

We have developed a system to estimate PV potential at city districts level 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.

To estimate solar irradiance rapidly 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. 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.

The rapid calculation of hourly solar irradiance of a grid point enables our new method to estimate PV potential more flexibly considering arrangement of solar panels corresponding to various settings of panel installing conditions such as width and height of a solar panel, and clearance around solar panels.

We conducted an experiment to evaluate impact of panel installing conditions on estimated PV potential in seven city districts in Japan. The experiment results indicate that minimum solar irradiance restriction would have the largest impact on PV potential among panel installing conditions. Lower margin restriction and clearance restriction would have an influence on PV potential. On the other hand an arrangement type and minimum number restriction of solar panels was not shown so important in PV potential estimation of façades in the experiment.

Our new method can estimate PV potential flexibly considering arrangement of solar panels corresponding to various settings of panel installing conditions. We consider that the flexibility of the method would be help one to make various scenarios of urban planning and energy management planning in a district.

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.

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, 2024. 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.

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

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.