Potential of Solar Energy Systems Considering Local Regulations and Roof Shapes

Obane Hideaki[*] · Sasakawa Akiko[**] · Morimoto Soichi[*] · Shibata Yoshiro[*] · Otsuki Takashi[***,*]

Abstract
Some of solar energy systems in Japan had a negative effect on the local environment and wildlife such as forest. Municipalities have recently regulated the installation of solar energy systems in these areas. If more solar energy systems are to be deployed in the future, it will be necessary to install them in areas with few or no competing uses or rooftops. However, the consideration of recent local regulations or characteristics of rooftops has been insufficient in previous studies assessing suitable areas for solar energy systems. Here, we show that the suitable area for solar energy systems is significantly reduced by considering these factors, in comparison with previous studies. We found that suitable areas for ground-mounted solar energy systems are significantly limited by composing a geoinformation database including regulation areas based on policy review for 263 municipalities. Furthermore, we found that available areas for rooftop solar energy systems are mainly in small buildings, where further cost reduction of solar energy systems is required. Our results demonstrate the importance of shifting ground-mounted solar energy systems to rooftop solar energy systems, and that the Japanese government should set appropriate targets or policies for the installation of rooftop solar energy systems.

Key words: Renewable energy, Solar energy, Energy policy, Spatial analysis, Photovoltaics

1. Introduction

Solar energy is being positioned as a major energy source for achieving carbon neutrality, and there are high expectations for its large-scale adoption. However, if solar energy systems were introduced on a large scale in the future, the issue of facing constraints on installation locations is predicted to become increasingly apparent.

By the end of March 2024, 57.9 GW of solar energy of 10 kW or more has been deployed[1)] through feed-in tariffs (FIT), while many solar energy systems have been installed in forests and other locations where there are concerns about the natural environment. The area for forest development that has been granted forest land development permits in connection with the installation of solar energy systems reached 171 km^2 by 2023,[2)] which is equivalent to approximately 11 GW when converted to solar energy generation capacity based on installation density,[3)] assuming power generation efficiency at the level when FIT was first introduced. This estimate suggests that at least one-sixth of the solar energy systems installed to date have been located in forests. In light of this situation, there has been a growing movement[4)] to regulate the installation of solar energy systems in specific locations in accordance with local regulations. In order to introduce solar energy on a large scale in the future, there is a need to identify the locations suitable for installing solar energy systems and clarify the feasibility of introducing solar energy systems toward achieving carbon neutrality.

To date, many studies and surveys have been conducted on the feasibility of introducing solar energy systems in Japan. For example, research on ground-mounted solar energy systems includes a study by Shimazaki[5)] and Ito et al. [6)] that focused on abandoned farmland, as well as surveys conducted by the Ministry of the Environment.[7)] There is also a study by Obane et al.[8)] that includes weedy land in addition to abandoned farmland as potential installation locations. However, previous studies have not fully considered the impact of regulatory ordinances, which have been expanding in recent years.

Research on rooftop solar energy systems includes that by Sugihara et al.[10)] and Wakeyama et al.,[11)] as well as surveys conducted by the Ministry of the Environment[7)], the New Energy and Industrial Technology Development Organization (NEDO),[12)] and the Japan Photovoltaic Energy Association (JPEA).[13)] In addition to these, there is also a study by Hirose et al.[14)] that organized the ideas in various literary references and visualized the differences in thinking and approach. For building roofs, unlike weedy land, it is necessary to take into account spaces that are unsuitable for installing solar energy systems due to the presence of outdoor air conditioner units and water tanks, for example. Previous studies drew up estimates based on the assumption that a certain percentage of the entire roof can be used for installing solar energy systems, such as by using the potential greening area of a model building[15)] as the basis for estimates. However, this posed the need for a more detailed assessment of roof characteristics.

* The Institute of Energy Economics, Japan
10th Floor Inui Bldg. Kachidoki, 13-1, Kachidoki 1-chome, Chuo-ku, Tokyo
Email: hideaki.obane@edmc.ieej.or.jp
** Affiliated with the Institute of Energy Economics, Japan at the time of writing
*** Associate Professor, Yokohama National University
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Therefore, this study aims to evaluate the feasibility of introducing solar energy systems. To that end, a geographic information system (GIS) was used to evaluate the potential of deploying ground-mounted and rooftop solar energy systems, based on a review of local regulations and an analysis of a database related to the deployment of solar energy systems in buildings.

The technical potential evaluated in this study is defined, in line with the definition provided by the Ministry of the Environment,[7] as the amount of energy available at the time of estimation, from among the energy reserves but excluding that which cannot be used due to various constraints related to energy collection and use. This study only takes into account land use and legal systems such as local regulations, while social constraints such as economic efficiency, grid constraints, and coordination with local communities were not considered. Furthermore, to align this study with the definition by the Ministry of the Environment, changes over time, such as a decrease in housing stocks, changes in land use, and improvements in power generation efficiency, were not taken into consideration.

2. Evaluation method

In this study, we constructed a GIS database that combined two types of data: land use data with an approximate 100 m mesh (3 seconds latitude by 4.5 seconds longitude) covering all of Japan except the Northern Territories. Based on this database, we then evaluated potential locations for installing solar energy systems. Fig. 1 provides an overview of the evaluation method.

Following the concepts presented by Obane et al., we classified Japan's land into 20 categories for ground-mounted solar energy systems, based on GIS data such as the National Land Numerical Information's "Land Use Subdivision Mesh Version 2.6, FY2016," "Forest Areas," "Agricultural Areas," and the Ministry of the Environment's "National Survey on the Natural Environment." These sections were then classified into four categories: weedy land, bare land, shrubby land, and degraded farmland that is difficult to rehabilitate. Furthermore, these land classifications exclude areas that are regulated under local regulations from the potential installation locations. Moreover, from among the potential installation locations for ground-mounted solar energy systems, land use competition is likely to arise with onshore wind energy systems in areas with good wind conditions. Therefore, locations with an annual average wind speed of 5.0 m/s or more at a height of 80 m above ground level were considered as areas of potential competition between ground-mounted solar energy systems and onshore wind energy systems.

For rooftop solar energy systems, evaluation was conducted based on FY2023 data from NTT InfraNet's GEOSPACE platform, which records the type and building area of each building. Detached houses are included in the building attribute "standard building" on GEOSPACE. However, since detached houses are not distinguished by a unique attribute, when estimating the roof area of detached houses, we used the "2018 Housing and Land Survey" published by the Ministry of Internal Affairs and Communications, which records the roof area of detached houses by prefecture.

Buildings other than detached houses were classified as public facilities or non-public facilities, and evaluated based on the roof area of the entire building as provided in the GIS data. However, the roof area provided in the GIS data includes spaces that are not suitable for installing solar energy systems, for example, due to the presence of water tanks. Therefore, by using a database of buildings that actually have solar energy systems installed, we estimated an installation coefficient for each building type, defined as the ratio of roof area to actual solar installation area. The area of potential locations for the installation of solar energy systems was then estimated based on this.

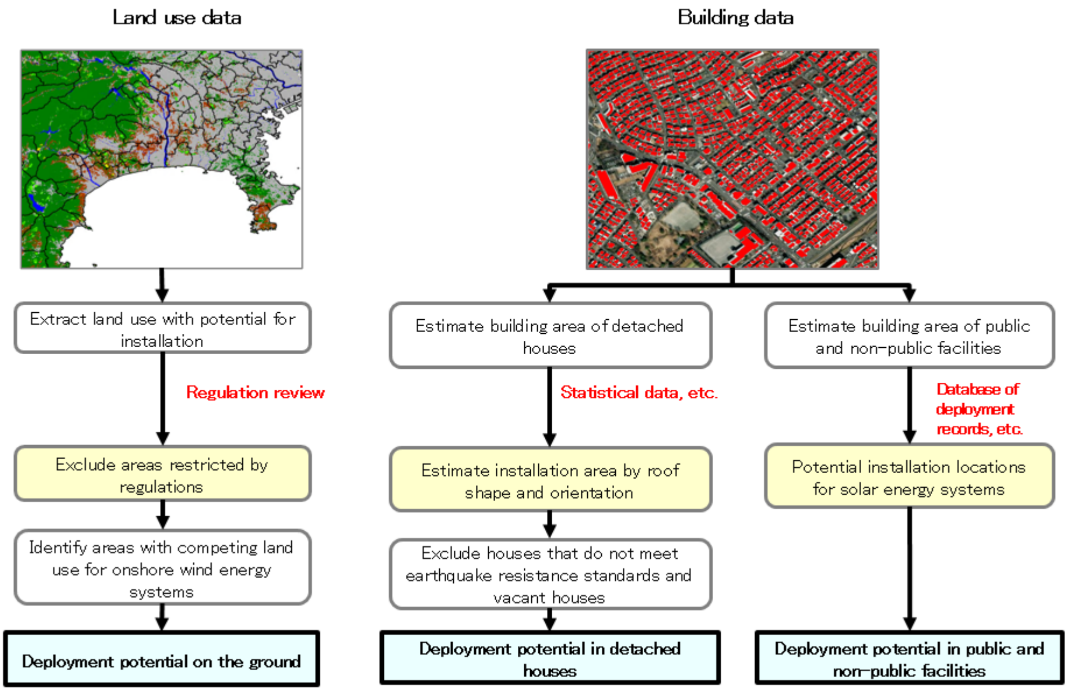


Fig. 1 Method of evaluating technical potential using a GIS database

3. Results of the evaluation of technical potential for ground-mounted solar energy systems

3.1 Area by land use

Fig. 2 shows the results of estimating area by land use based on a GIS database. According to the GIS database, the total land area of Japan, excluding the Northern Territories, is 372,835 km^2. Land use areas on which it is difficult to install ground-mounted solar energy systems, such as protected forests and farmland, make up 50% of the country's land area, while land classifications in which installation is not recommended from the perspective of environmental conservation, such as privately owned forests and national forests, account for 47% of the total. Buildings with potential for the installation of rooftop solar energy systems, which will be detailed later, comprise 2% of the total.

The total area of weedy land, bare land, shrubby land, and degraded farmland that is difficult to rehabilitate, which are areas with potential for the installation of ground-mounted solar energy systems, is estimated to be 4,887 km^2, which is equivalent to 1% of the total. However, this area does not take into account areas subject to local regulations; if such areas were considered, the number of potential locations for installing ground-mounted solar energy systems would be further reduced.

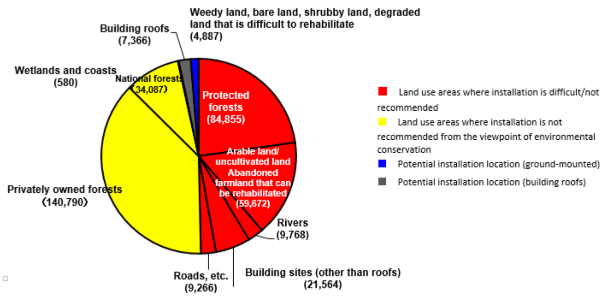


Fig. 2 Area by land use [km^2]

3.2 Results of the extraction of areas subject to local regulations

In order to consider areas subject to local regulations, we conducted a review of the regulations enacted by 263 of the 1,718 municipalities nationwide that were confirmed to have established regulations pertaining to solar energy up to March 2024, taking reference from the Research Institute for Local Government.[4)] As a result, within the scope of information available on each municipality's website, 195 municipalities were found to have designated specific legal zones, and a further 12 municipalities regulate the installation of solar energy systems throughout the entire municipality. It was also confirmed that the remaining 56 municipalities have enacted regulations that only regulate aspects such as construction methods and scale of installation.

This study only covers municipalities that have clearly specified areas that specifically restrict the installation of solar energy systems, such as restricted zones, and the classifications of such areas were then extracted. The results are shown in Fig. 3, which shows the areas designated as restricted zones in order of municipalities with the highest number of designated zones. Of these, the blue bars indicate areas for which GIS data was confirmed and that were taken into account in the GIS database, while gray bars indicate areas for which GIS data could not be confirmed.

Areas subject to regulation, such as restricted zones, include areas designated for disaster prevention, areas related to the conservation of the natural environment, and areas related to landscape conservation, among others. These areas are considered to be areas where the installation of solar energy systems is not recommended, regardless of whether any regulations have been put in place. For this reason, in this study, areas extracted from all municipalities were excluded from the potential installation locations, regardless of whether the respective municipalities had actually enacted any regulations.

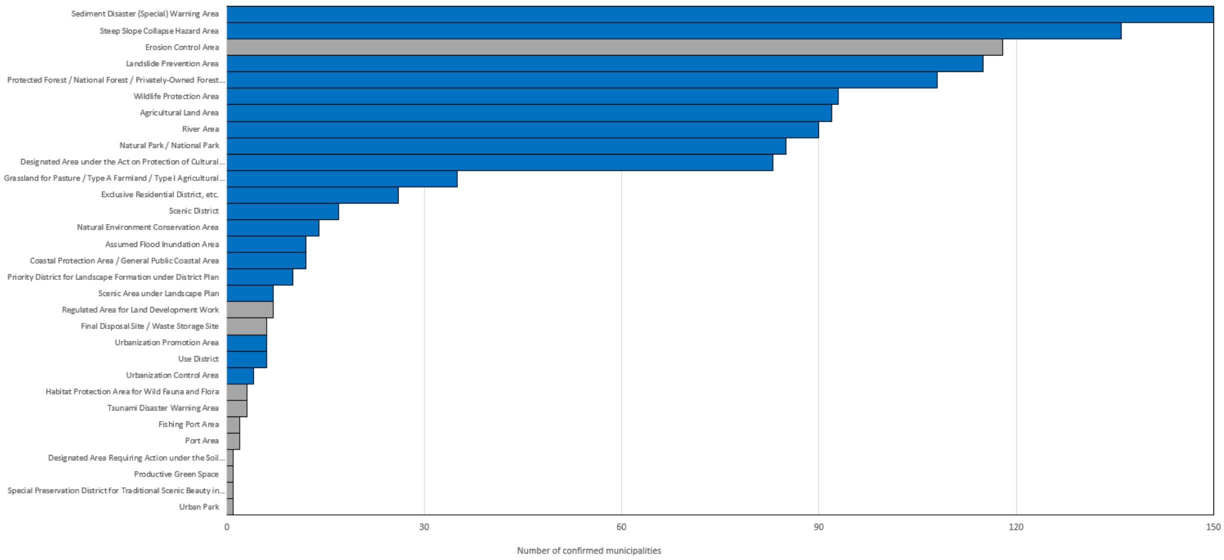


Fig. 3 Areas designated as restricted zones (in order of municipalities with the highest number of designated zones)

3.3 Area of potential installation locations, taking local regulations into account

Of the land use areas with potential for the installation of ground-mounted solar energy systems (4,887 km^2), such as weedy land, Fig. 4 shows the results that exclude areas subject to local regulations in all municipalities, in order from the municipalities with the highest number of areas.

The results show that, in the most conservative case, where all areas subject to local regulations are excluded, the area of potential installation locations was significantly reduced to 383 km^2. In this study, this is described as the "case excluding all restricted zones." In such cases, landscape planning areas contribute the most to the reduction in area. Landscape planning areas have designated restrictions on activities for the purpose of creating favorable landscapes, and it has been confirmed that at least eight municipalities have designated such areas as restricted zones by the end of FY2023. Although it is not necessarily the case that the installation of solar energy systems is prohibited in all landscape planning areas across Japan, it is difficult to quantify the installation capacity of solar energy systems that can be installed in such areas while giving consideration to specific circumstances. Therefore, a case that includes only areas designated as restricted zones by a larger number of municipalities than those designated as landscape planning areas among the potential installation locations is separately defined as the "case with partial exclusion of restricted zones." The area of the potential installation locations in such cases was estimated to be 3,250 km^2.

Fig. 5 shows the potential installation locations by municipality for each case. In (A) case with partial exclusion of restricted zones, many of the potential installation locations are concentrated in the plains of Hokkaido. However, as the whole of Hokkaido has been designated as a landscape planning area, in (B) case, excluding all restricted zones, the results show that there are potential installation locations in some municipalities in the Tohoku, Hokuriku, and Chugoku regions.

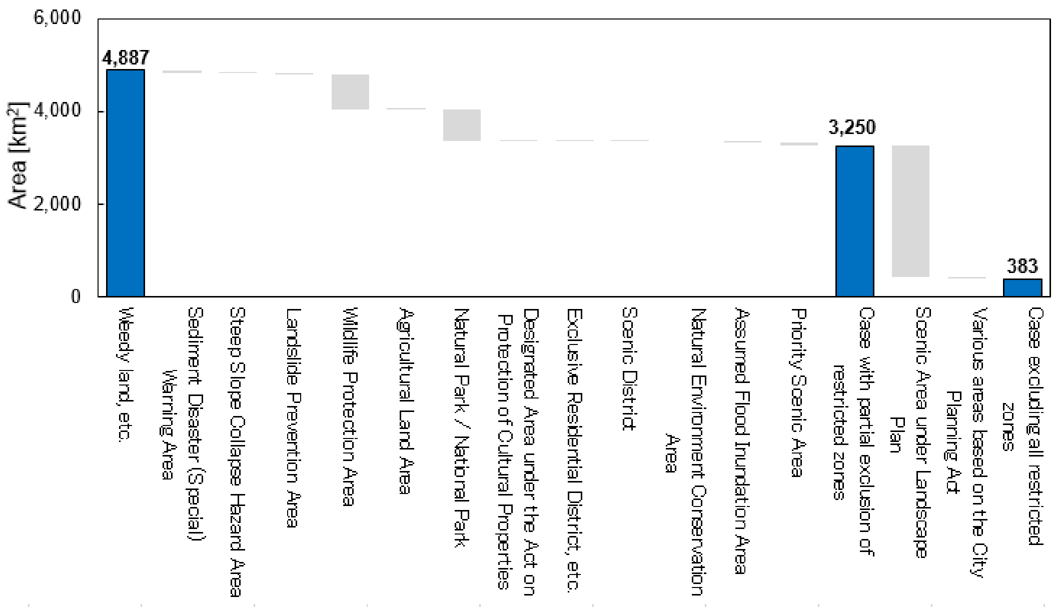
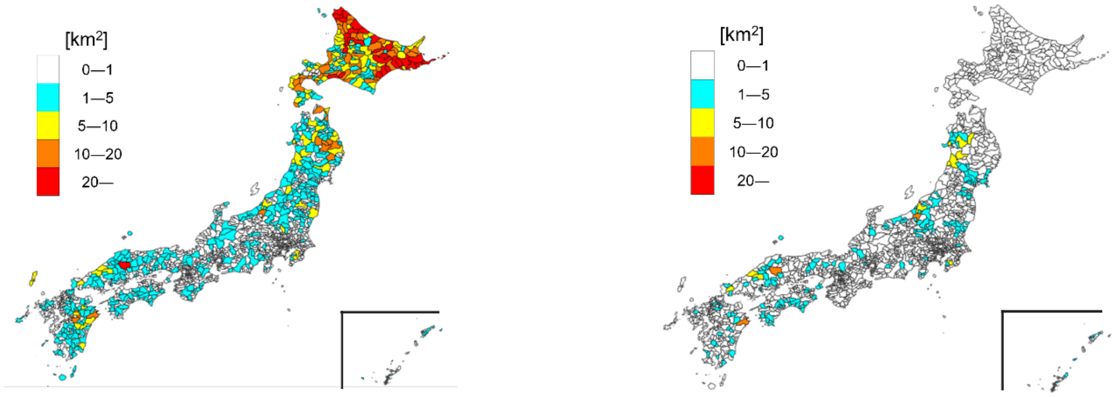


Fig. 4 Area excluding restricted zones in order of frequency [km^2]



(A) Case with partial exclusion of restricted zones (B) Case excluding all restricted zones

Fig. 5 Area of potential installation locations for ground-mounted solar energy systems by municipality [km^2]

3.4 Technical potential that takes into account competing land use with onshore wind energy systems

Of the potential installation locations for the two cases defined in the previous section, the areas of locations where land use competition occurs with onshore wind energy systems due to annual average wind speeds of 5.0 m/s or more, and of locations with wind speeds of less than 5.0 m/s, were estimated. These were then converted to technical potential based on an installation density of 0.111 GW/km^2 (ground-mounted solar energy system) and 0.010 GW/km^2 (onshore wind energy system), in line with the Ministry of the Environment.[7)]

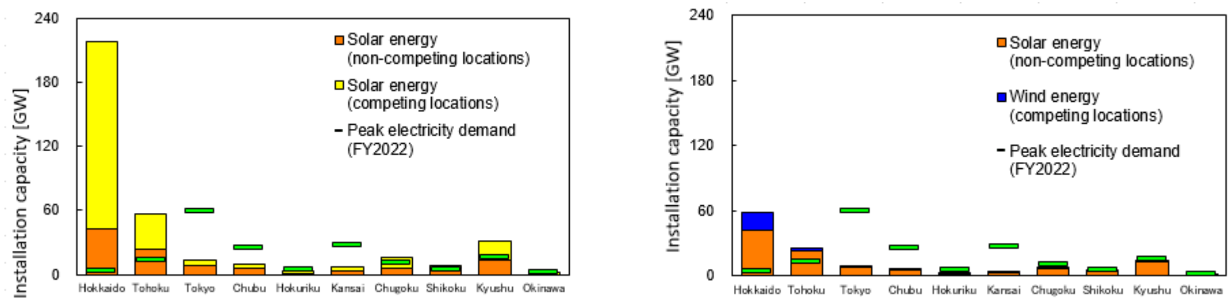
Table 1 shows the technical potential under the conditions described above, considering land use competition with onshore wind energy systems. First, if a solar energy system were to be installed in a location where there is no competition with onshore wind energy systems, the technical potential was estimated to be 20 GW (case excluding all restricted zones) and 107 GW (case with partial exclusion of restricted zones). If a solar energy system were to be installed beyond this installation capacity, it would then be necessary to take into consideration competing land use with onshore wind energy systems.

The areas that compete with onshore wind energy systems were estimated to be 2,283 km^2 and 206 km^2 in the case with partial exclusion of restricted zones and case excluding all restricted zones, respectively. Hypothetically, if solar energy systems were installed in all competing locations, the maximum installation capacity would be 253 GW and 23 GW, respectively.

Therefore, if we were to carry out a simple comparison of the amount of power generated in order to consider the energy source suitable for the competing locations, in the competing locations in the case with partial exclusion of restricted zones, 133 TWh of power would be generated from a 253 GW-solar energy system (converted at capacity factor of 14%), while 61 TWh of power would be generated from a 23 GW-onshore wind energy system (converted at capacity factor of 30%). Hence, if we were to consider only the amount of power generated, it would be more advantageous to install solar energy systems at all competing locations. However, looking at the results of a comparison of the technical potential by the power area and peak electricity demand in FY2022 (Fig. 6), we can see that if solar energy systems were installed at all competing locations, peak electricity demand in FY2022 would be significantly exceeded in Hokkaido, Tohoku, Kyushu, and other regions. In addition to ground-mounted solar energy systems, the technical potential of rooftop solar energy systems, which will be detailed later, is also added. Therefore, if solar energy systems, which only generate electricity during the day, were deployed on a large scale beyond the peak electricity demand, there would be a need to put in place measures such as installing storage batteries and reinforcing interconnection lines. For this reason, it is necessary to determine the energy source suitable for competing locations by considering the balance of electricity supply and demand in each time period.

Table 1　Area of potential installation locations for solar energy systems and technical potential, taking into account competing land use with onshore wind energy systems

Case	Competition with onshore wind energy systems	Area [km^2]	Technical potential [GW]	
Case with partial exclusion of restricted zones	Competing locations	2,283	Solar energy Onshore wind energy	0 – 253 0 – 23
	Non-competing locations	967	Solar energy	107
Case excluding all restricted zones	Competing locations	206	Solar energy Onshore wind energy	0 – 23 0 – 2
	Non-competing locations	177	Solar energy	20



(A)　Case of installing solar energy systems in all competing locations

(B)　Case of installing onshore wind energy systems in all competing locations

Fig. 6　Comparison of technical potential and peak electricity demand by power areas (case with partial exclusion of restricted zones) [GW]

4.　Results of evaluation of technical potential for detached houses

4.1 Area that takes into account roof shapes

The building area of detached houses in the GIS database was 2,238 km^2. However, since this area is a projected area as viewed from above, the shapes and orientation of roofs are not taken into consideration. Therefore, the roof angle was adjusted to the angle of 5-inch roofs (26.6 degrees), which cover the largest number of houses, and the area of each type of roof was estimated for each power area based on data on the percentage of roofs by region from the Japan Housing Finance Agency[16] (Fig. 7). The results show that gable roofs composed of two roof surfaces, hipped roofs composed of four roof surfaces, and shed roofs composed of a single roof surface, make up the majority of roof types in Japan.

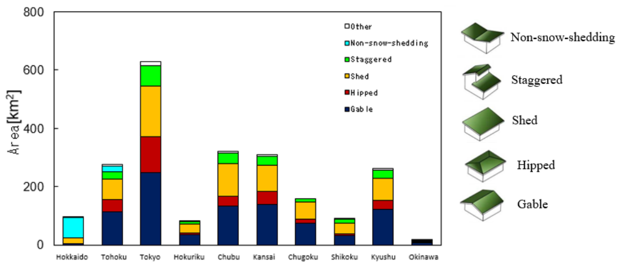


Fig. 7　Area by type of roof on detached houses[km^2]
(Source for the figure: CONOIRO (Yuko Navi) [17])

4.2 Installation coefficients by type of roof

Based on the area of each type of roof, we considered the installation coefficient (the ratio of the roof area to the area available for installing solar power system) for each type of roof. Previous studies on installation coefficients have been conducted by the Japan Science and Technology Agency (JST)[18] and the Ministry of the Environment.[3] JST presented the installation coefficients for the total of all orientations for 103 flat roofs, 30 hipped roofs, and 74 gable roofs as 0.65 to 0.8, 0.65 to 0.7, and 0.7 to 0.85, respectively. The minimum installation coefficient is defined as the current standard value, while the maximum is defined as a high level based on the assumption of maximum installation in the future. On the other hand, the Ministry of the Environment has set out the installation coefficients for each orientation based on three sample roofs for a total of six roof types, and the installation coefficients for the total of all orientations are 0.34 for flat roofs, 0.68 for hip roofs, and 0.60 for gable roofs.

Comparing the installation coefficients presented by JST and the Ministry of the Environment, we can see a significant discrepancy, particularly for flat roofs; this is presumably because JST includes roofs other than those of detached houses in its sample survey. Therefore, this study takes reference from the installation coefficients by angle prepared by the Ministry of the Environment, which determined installation coefficients by roof type and orientation as shown in Table 2. Note that for staggered roofs and other types of roofs, the installation coefficients for gable roofs were applied due to the lack of available sample data.

Based on these installation coefficients, the roof areas by orientation, estimated by power area, are shown in Fig. 8. The total area occupied by the space around solar cell modules in all detached houses was estimated to be 773 km^2, and the area of the remaining installation locations, which excludes such space from the total roof area, was estimated to be 1,465 km^2.

Table 2 Installation coefficients for detached houses, by orientation

Type of roof	South	East-West	North
Gable	0.15	0.3	0.15
Hipped	0.17	0.34	0.17
Irimoya (hip-and-gable)	0.14	0.27	0.14
Flat	0.34	0	0
Shed	0.12	0.25	0.12
Staggered	0.15	0.3	0.15
Non-snow-shedding	0.215	0.435	0.215
Other	0.15	0.3	0.15

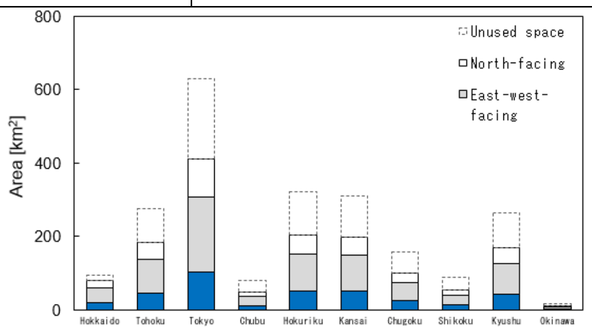


Fig. 8 Area of detached house roofs by orientation [km^2]

4.3 Technical potential that takes into account houses that do not meet earthquake resistance standards and vacant houses

The installation of solar energy systems is not recommended for detached houses that do not meet earthquake resistance standards based on the Building Standards Act revised in June 1981 (new earthquake resistance standards). Therefore, taking reference from the stance of NEDO[12)] and Table 171-1 of the "2018 Housing and Land Survey" published by the Ministry of Internal Affairs and Communications, we estimated the percentage of detached houses in each prefecture that do not meet the new earthquake resistance standards, and excluded them from the houses for which installation is feasible.

Furthermore, while it is not necessarily impossible to install solar energy systems in vacant houses, it may affect the management of solar energy systems.. However, since there is a possibility that houses built before 1980 may overlap with houses that do not meet the new earthquake resistance standards, we used Table 235-2 of the "2018 Housing and Land Survey" to estimate the percentage of vacant houses built after 1981 by building age and prefecture, and excluded these from the houses for which installation is feasible.

Following the above approach, the building area of detached houses was estimated, excluding the space around the solar cell modules described in the previous section, the area of houses that do not meet the new earthquake resistance standards, and vacant houses. The results are shown in Fig. 9. The total area of potential installation locations across all orientations was estimated to be 1,169 km^2. Based on this result, the technical potential by orientation was estimated to be 49.2 GW (south-facing), 97.1 GW (east-west-facing), and 48.0 GW (north-facing). Of these, south-facing roofs, which generate the most electricity, accounted for about one-quarter of the total technical potential (Table 3).

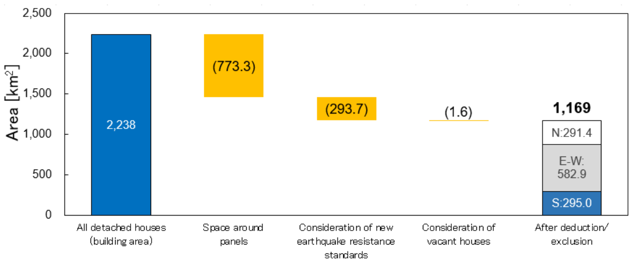


Fig. 9 Area of installation locations for detached houses, taking into account houses that do not meet the new earthquake resistance standards and vacant houses [km^2]

Table 3 Area of installation locations by orientation, and technical potential

Orientation	Area [km^2]	Technical potential [GW]
South	291.4	49.2
East-West	582.9	97.1
North	295.0	48.0
Total	1,169	194.4

5. Results of evaluation of technical potential in public and non-public facilities

5.1 Installation coefficient

The building areas of non-public and public facilities in the GIS database were 4,759 km^2 and 368 km^2, respectively. However, these areas represent the total roof areas and exclude roof spaces unsuitable for solar energy systems, such as those with water tanks and outdoor air conditioning units.

In previous studies,[3), 7), 12)] based on the concept of potential greening areas of model buildings,[15)] the percentage of the roof area excluding cooling tanks and water tanks was determined to be 86%, the remaining area excluding security spaces that must be secured was 58%, and 49.9% of all building roofs (installation coefficient 0.499) could have solar energy systems installed. However, in light of the increasing number of solar energy system installations in recent years, this study estimated the installation coefficient based on the estimated the installation coefficient using actual deployment data by building type, based on the JABMEE ZEB database containing information on buildings with solar energy systems installed, as well as data from the Ministry of the Environment,[19)] which conducted a sampling survey using satellite images. (Table 4)

For standard buildings such as offices and office buildings, the installation coefficients were estimated using the JABMEE ZEB database. This database contains information such as the addresses of buildings that are classified as Zero Emission Buildings (ZEB), Nearly ZEB, and ZEB Ready, as well as the rated output of solar energy systems, roof area, and area for the installation of solar energy systems. As of October 2024, data for 43 buildings have been included, of which data was extracted from 20 buildings that fall under the categories of "offices, etc." and "other" and which have only rooftop solar energy systems installed (excluding wall-mounted systems). The installation coefficient was then estimated based on the ratio of the area where solar energy systems have been installed to the roof area. For buildings with no indication of the solar energy system installation area, the installation area was estimated using Google Maps based on the building address.

Fig. 10 shows the frequency distribution of the installation coefficients in the JABMEE ZEB database. The results show that the average value of the installation coefficients for the 20 cases was 0.263 with a maximum value of 0.59, a minimum value of 0.02, and a standard deviation of 0.18. The buildings included in the database are based on the premise of being ZEBs, and it is likely that the maximum possible roof area is being utilized. In this study, the average installation coefficient value from the same database, 0.263, was applied

For non-standard buildings, the installation coefficient (0.079 to 0.388) was calculated by the Ministry of the Environment[19)] for each type of building based on Table 5.6-4, and used as a premise for the estimation.

Table 4 Samples used as the basis for calculating installation coefficients

Building	Sample used as the basis for calculating installation coefficients
Public offices	14 samples corresponding to “prefectural/municipal offices” and “public agencies, etc.”
Hospitals	25 samples corresponding to “hospitals”
Schools	176 samples corresponding to “schools”
Defense facilities	31 samples corresponding to “other public facilities”
Housing complexes	2 samples corresponding to “housing complexes”
Factories	6 samples corresponding to “leisure facilities,” “sports facilities,” and “other facilities”
Leisure/Commercial facilities	
Accommodation facilities	
Markets	
Warehouses	
Gas stations	
Standard buildings	20 samples corresponding to “places of business, etc.” and “other” in the JABMEE database

※ Estimated for non-standard buildings based on Table 5.6-4 (Ministry of the Environment[19)])

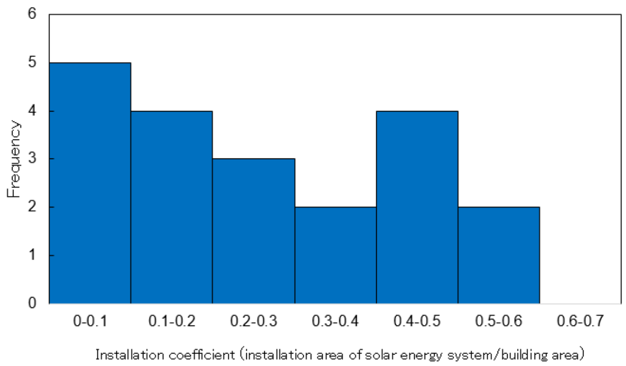


Fig. 10 Frequency of installation coefficients for buildings that correspond to "places of business, etc." and "other" in the JABMEE database

5.2 Technical potential that reflects the installation coefficients

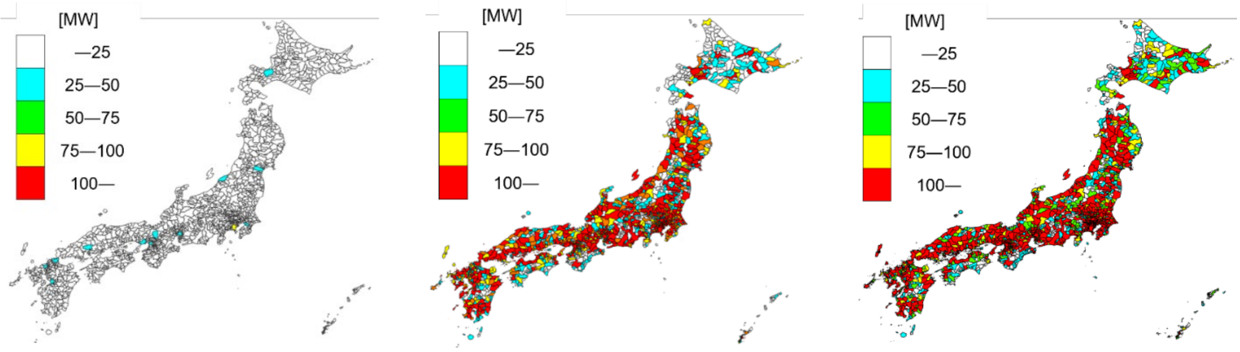
Table 5 shows the estimates for the area of potential installation locations for solar energy systems in public and non-public facilities, and their technical potential, calculated using the installation coefficients shown in the previous section. In the table, the left column shows the roof area estimated using the GIS database, and the middle column shows the results of estimations drawn up on the area of potential installation locations for solar energy systems and their technical potential, using installation coefficients based on the actual deployment of solar energy systems from the JABMEE database and other data sources. The right column shows the results of estimations drawn up for the area of potential installation locations and their installation capacity, using an installation coefficient of 0.499 based on the concept of potential greening area, as in previous research.

According to the results, of the total of 5,128 km^2 for non-public and public facilities estimated in the GIS database, the area was 1,236 km^2 when estimated based on the actual solar energy systems deployed. This was 137.2 GW when converted to technical potential. On the other hand, when estimation is carried out based on the conventional approach of potential greening area, the technical potential becomes 284.0 GW. Therefore, the technical potential estimated using the potential greening area approach is 146.8 GW larger than that based on actual solar system deployment.

Fig. 11 shows estimates for the technical potential for rooftop solar energy systems by municipality, using the installation coefficient based on the actual solar energy systems deployed. In addition to the public and non-public facilities discussed in this chapter, Fig. 11 also shows the area of potential installation locations (south and east-west installations only) in detached houses estimated in Chapter 4. First, focusing on public facilities where the mandatory installation of solar energy systems is already being considered in some areas, the installation capacity of each municipality is only a few tens of MW. This indicates that the installation capacity of solar energy systems is limited compared to non-public facilities and detached houses. On the other hand, for non-public facilities and detached houses, the results show that the installation capacity for many municipalities is more than 100 MW, suggesting that if the deployment of solar energy systems were expanded, it would be more important to introduce them in existing detached houses and non-public facilities.

Table 5 Area of potential installation locations in public and non-public facilities [km^2] and technical potential (installation capacity) [GW]

	Roof area [km^2]	Based on actual solar energy systems deployed			Based on potential greening area		
		Installation coefficient	Area of potential installation location [km^2]	Installation capacity [GW]	Installation coefficient	Area of potential installation location [km^2]	Installation capacity [GW]
Public offices	106	0.079	8.4	0.9	0.499	53	5.9
Hospitals	50	0.100	5.0	0.6		25	2.8
Schools	198	0.109	21.5	2.4		99	10.9
Defense facilities	15	0.071	1.0	0.1		7	0.8
Total for public facilities	368		36	4.0		184	20.4
Housing complexes	153	0.388	59.3	6.6	0.499	76	8.5
Factories	380	0.167	63.5	7.0		190	21.0
Warehouses	81	0.167	13.6	1.5		41	4.5
Leisure/Commercial facilities	249	0.167	41.6	4.6		124	13.8
Accommodation facilities	20	0.167	3.3	0.4		10	1.1
Markets	6	0.167	1.0	0.1		3	0.3
Gas stations	5	0.167	0.8	0.1		3	0.3
Standard buildings	3,865	0.263	1,017	112.8		1,929	214.1
Total for non-public facilities	4,759		1,200	133.2		2,375	264.0
Total	5,128		1,236	137.2		2,559	284.0



(A) Public facilities (B) Non-public facilities (C) Detached houses

Fig. 11 Technical potential for rooftop solar energy systems by municipality [MW] (estimated using installation coefficients based on actual solar energy systems deployed)

5.3 Technical potential by area of individual buildings

In order to understand the installation locations of public and non-public facilities in greater detail, the technical potential by roof area for each individual building was estimated and the results are shown in Fig. 12. In the figure, the horizontal axis shows the roof area per building obtained from the GIS database, and the vertical axis shows the estimated technical potential for each roof area range, using installation coefficients based on the actual solar energy systems deployed.

The results show the total technical potential for solar energy systems in buildings with roof areas between 0 to 99 m^2 and 100 to 199 m^2 is 60.4 GW, indicating that approximately half of the total technical potential for solar energy systems (137.2 GW) is concentrated in buildings with small roof areas. For buildings with roof areas of less than 199 m^2, even if solar energy systems were installed in ways that make the most of the building area, the installation capacity would be small, approximately 20 kW. Therefore, when encouraging the introduction of solar energy systems on the roofs of public and non-public facilities, it is important to install such systems on small-scale buildings.

According to Japan's Procurement Price Calculation Committee,[20] the system cost for a 500 to 1,000 kW solar energy system installed in 2023 is 147,000 yen/kW, in contrast with the cost of 251,000 yen/kW for a 10 to 50 kW facility. This is a discrepancy of approximately 1.7 times due to the difference in the scale of the systems. Currently, some large-scale solar energy systems of 1,000 kW or more do not receive support in the form of subsidies, such as in cases where the supply price in Feed in Premium (FIP) bidding is 0 yen/kWh[21]. However, with local regulations limiting the locations where solar energy systems can be installed on the ground, it will be necessary to reduce the installation costs even for systems of a smaller scale in order to promote the installation of solar energy systems on building roofs.

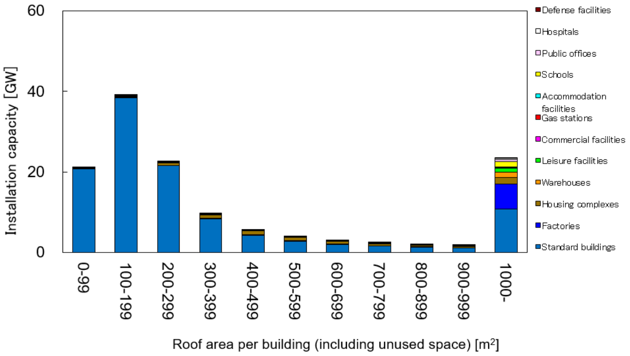


Fig. 12 Technical potential per building, by roof area [GW]

6. Conclusion

This study evaluated the technical potential of solar energy systems, taking into consideration local regulations and roof shapes. The findings and contributions of this study are summarized below.

Firstly, compared to the conventional approach to evaluating the technical potential for ground-mounted solar energy systems, this study demonstrates that the number of potential installation locations for ground-mounted solar energy systems is significantly reduced when areas that may be subject to local regulations are taken into consideration as a constraint. Until now, solar energy systems have been installed in places where there are concerns about disasters or the impact on the natural environment, such as forests and steep slopes. However, if the aim is to expand the introduction of solar energy in the future, it would be desirable to prioritize its installation on buildings. Furthermore, each restricted zone identified in this study is considered unsuitable for installing solar energy systems, regardless of whether local regulations are in place, regardless of whether regulations have actually been enacted. Therefore, this is expected to serve as basic information for the establishment of regulations by municipalities that do not currently have such regulations in place.

Secondly, with regard to detached houses, which are considered as one of the potential targets for the future expansion of solar energy system deployment, the technical potential for all orientations based on installation capacity is generally consistent with the evaluation results obtained in previous studies (167 to 201 GW).[7), 13)] However, when the orientation of the roof is taken into consideration, it was shown that the technical potential for south-facing roofs, which generate the most electricity, is only about one-quarter of the total, while the remaining half is for east-west-facing roofs. Therefore, when establishing national targets for the introduction of solar energy systems, it is necessary to account for the differences in power generation across orientations. Moreover, since the peak power generation differs depending on the orientation, the technical potential by orientation can also be used as basic information when conducting quantitative analysis using energy system models, etc.

Thirdly, by employing a method of estimating the feasible area for installing solar energy systems based on the actual solar energy systems deployed for both public and non-public facilities, this study showed that south-facing roofs, which generate the most electricity, account for only about one-quarter of the total technical potential, while approximately half is from east-west-facing roofs. When referring to the technical potential in establishing solar energy system installation targets, it is important to compare estimates based on different approaches. In addition, as approximately half of these potential installation locations are small-scale buildings, it is important to reduce installation costs for solar energy systems on buildings with small roofs.

In further refining the evaluation of technical potential for solar energy systems, one of the challenges is refining the installation coefficient. Current issues include the limited number of samples used to estimate the installation coefficient, the fact that buildings such as rooftop heliports without solar energy systems are not included in the sample, and the fact that it is based only on the actual deployment results of silicon-based solar energy systems that are in practical use. In order to evaluate the technical potential with greater precision in the future, it will be necessary to collect more current installation coefficients related to the calculation of the installation coefficient, as well as more examples of roofs.

While there are challenges in further refining the technical potential, it is expected that the risk of overestimating the technical potential of solar energy systems will be reduced by considering local regulations and roof shapes. Therefore, the approach to evaluating the technical potential presented in this study is expected to contribute to the establishment of solar energy promotion policies and deployment targets.

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Contact: report@tky.ieej.or.jp