

# Chapter 36

## Framework for Calculating the Rooftop Solar Photovoltaic (PV) Footprint Considering Building Electricity Supply and Demand from the Urban Level



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### 36.1 Introduction

Ever since the industrial revolution, electricity supply always has been a great issue for energy security and economic growth in all over the world [1]. However, conventional energy sources for supplying electricity, fossil fuels such as coal, oil, and gas, are the biggest contributors to climate change and global warming which threaten human healths and environments [2]. Recent concerns on climate change and environmental pollution had led to the emergence of renewable energy, and various efforts for promoting these technologies are made over the past few decades [3].

This new energy paradigm shift from fossil fuels to renewable energy brought a concept of energy “prosumer” through distributed solar generation (DSG). An energy “prosumer,” who can both produce and consume energy, makes it possible to increase the market penetration through DSG, on-site electricity generation from solar energy (i.e., rooftop solar photovoltaic (PV) system). They can also sell the surplus electricity back to the grid for supplying electricity to their neighborhoods to meet the urban-level electricity demand [4]. In this regard, to successfully implement DSG and ultimately achieve nearly zero-energy building (nZEB) from the urban level, it is crucial to analyze and determine how much electricity from DSG is required to offset the urban-level electricity demand. This can be done by analyzing and investigating the electricity supply (i.e., electricity generated from DSG) and demand (i.e., electricity consumed in buildings) of each individual building in the neighborhood [5].

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To analyze the relationship of the electricity supply and demand effectively and strategically, this study applied the “ecological footprint” approach to DSG by introducing the rooftop solar PV footprint, the total rooftop area required for DSG to meet building electricity demand [5]. From the energy usage aspect, the relationship of the electricity supply and demand can be analyzed by using the self-sufficiency rate of electricity. This self-sufficiency rate indicates the proportion of locally produced electricity from DSG to consumed electricity in buildings [6]. However, as mentioned above, the self-sufficiency rate can only provide some information on how the electricity from DSG has been used locally. Instead, the rooftop solar PV footprint can provide some plans and strategies on how the rooftops could be utilized for installing DSG from the rooftop usage aspect. Therefore, the rooftop solar PV footprint could be very useful for planning future energy policies and strategies from the urban level.

Regarding this issue, several previous studies were conducted to investigate the relationship of the building electricity supply and demand [5–8]. However, most of the previous studies mainly focused on analyzing the building electricity supply and demand by the self-sufficiency. There was almost no study dealing with the concept of solar PV footprint.

Therefore, this study aims to propose a framework for calculating the rooftop solar PV footprint by considering building electricity supply and demand from the urban level. Toward this end, the methods for calculating the available rooftop area, rooftop solar PV potential, and rooftop solar PV footprint were suggested in stages using building information, solar radiation, and energy consumption data based on geographical information system (GIS). The proposed framework was applied to Yeoksam-dong and Samseong-dong in the Gangnam District, Seoul, South Korea, a popular metropolitan area where high-rise office buildings abound, to show and compare the analysis results.

## 36.2 Materials and Methods

This study proposed a framework for calculating the rooftop solar PV footprint in four steps (refer to Fig. 36.1): (i) step 1, establishment of the database; (ii) step 2, calculation of the available rooftop area; (iii) step 3, calculation of the rooftop solar PV potential; and (iv) step 4, calculation of the rooftop solar PV footprint.

### 36.2.1 Step 1: Establishment of the Database

In step 1, the database on the building information, solar radiation, and energy consumption should be established to ultimately calculate the rooftop solar PV footprint. First, the building information data should be collected to calculate the available rooftop area using the Hillshade analysis. Building information data such

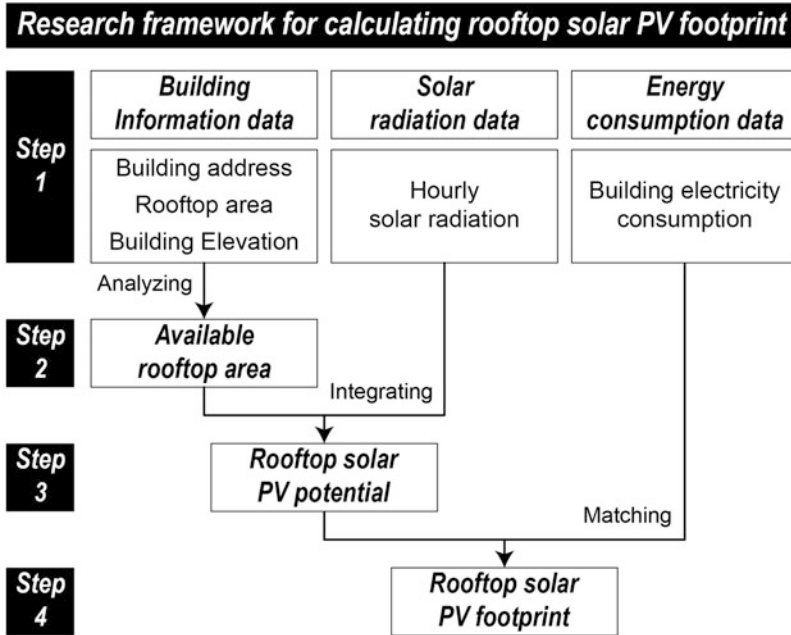


Fig. 36.1 Research framework

as building address and rooftop area and building elevation in South Korea can be collected from a foundation corporation called Spatial Information Industry Promotion Institute (SPACEN) under the Ministry of Land, Infrastructure, and Transport (MOLIT) of the Korean government [9]. These building information data, particularly the building elevation data, are used to calculate the available rooftop area for solar PV installation by excluding the shaded rooftop area.

Second, the solar radiation data should be collected to calculate the rooftop solar PV potential. Since this study proposed a calculation method of the rooftop solar PV potential on an hourly basis, this study needed the hourly solar radiation data. The hourly solar radiation data in Seoul can be collected from the World Radiation Data Centre (WRDC), sponsored by the World Meteorological Organization [10].

### 36.2.2 Step 2: Calculation of the Available Rooftop Area

In step 2, the available rooftop area for solar PV installation should be calculated to analyze the practical and realistic rooftop solar PV potential. First, the shaded rooftop area should be calculated based on the altitude and azimuth of the sun using the Hillshade analysis. To calculate the shaded area using the Hillshade analysis, it requires two types of input data. First, the building spatial data with

elevation information, which can be collected in step 1, is needed. Second, the location data of the sun, specifically the altitude and azimuth of the sun at the time of the analysis, is needed. The altitude and azimuth of the sun at any time in South Korea can be calculated using the Sun Altitude and Azimuth Calculation tool from Korea Astronomy and Space Science Institute (KASI) [11]. By using these input data, Hillshade analysis can be conducted using the ArcGIS, a GIS software by the Environmental Systems Research Institute (ESRI) [12].

Second, the available rooftop area should be calculated by excluding the shaded and small rooftop area. First, the shaded rooftop area should be excluded from the total rooftop area based on the Hillshade analysis results. By excluding the shaded rooftop area, it is possible to quantify the rooftop area where DSG can perform at the optimal level without any disturbance of the building shadow. Second, the small rooftop area where it is hard to install DSG should be additionally excluded. The rooftop area below 33 m<sup>2</sup> should be excluded from the available rooftop area, since the Korea New and Renewable Energy Center (KNREC) requires at least 33 m<sup>2</sup> in rooftop area for installing a 1-kW DSG [13].

### ***36.2.3 Step 3: Calculation of the Rooftop Solar PV Potential***

In step 3, the rooftop solar PV potential considering the available rooftop area should be calculated to analyze the practical and realistic rooftop solar PV potential. First, the solar PV module efficiency should be defined to analyze the rooftop solar PV potential. Although the solar PV module efficiency varies depending on the different types and manufacturers of solar panels [14], the efficiency of the commercial solar PV modules usually ranges from 15% to 18% [15]. By using the solar PV module efficiency between this range for calculating the technical potential of the rooftop solar PV system, it is possible to reflect the current technology level of the solar PV market and industry.

Second, the installed condition of DSG should be also determined to analyze the rooftop solar PV potential. Since this study proposed a calculation method of the rooftop solar PV potential on an hourly basis, the available rooftop area where DSG can perform at the optimal level without any disturbance of the building shadow changes by time. Accordingly, to fully consider the difference in the available rooftop area by time and calculate the rooftop solar PV potential on an hourly basis, this study assumed that the solar PV panels are installed horizontally with no tilt on the entire rooftops [3].

### ***36.2.4 Step 4: Calculation of the Rooftop Solar PV Footprint***

In step 4, the rooftop solar PV footprint should be calculated by matching and integrating the rooftop solar PV potential and energy consumption data of the

individual building. To match these two data from the different data source, it is necessary to define the identification reference to be based on for combining the two different data of the same building together. Since the building is managed based on its official address in South Korea, this study used the official building address for matching the rooftop solar PV potential and energy consumption data of a building.

### 36.3 Numerical Scheme

The rooftop solar PV potential and footprint explained in steps 3 and 4 can be calculated using Eqs. (36.1) and (36.2). By integrating the available rooftop area estimated through the process in step 2 with the hourly solar radiation data, it is possible to calculate the rooftop solar PV potential on an hourly basis [3]. By matching the rooftop solar PV potential per unit rooftop area with the energy consumption data of each individual building, it is possible to calculate the rooftop solar PV footprint of a building.

$$RSPP = e_{PV} \times \sum_{i=1}^{12} \left( \sum_{j=6}^{18} (ARA_{ij} \times SR_{ij}) \right) \quad (36.1)$$

$$RSPF = \frac{EC}{RSPP/RA} \quad (36.2)$$

where  $RSPP$  stands for the rooftop solar PV potential of a given building for a year (kWh),  $e_{PV}$  stands for the solar PV module efficiency,  $ARA_{ij}$  stands for the available rooftop area of a given building on the fifteenth of month  $i$  at time  $j$  to  $j + 1$  ( $m^2$ ),  $SR_{ij}$  stands for the total solar radiation on month  $i$  at time  $j$  to  $j + 1$  ( $kWh/m^2$ ),  $i$  stands for the month ( $i = 1, 2, 3, \dots, 12$ ),  $j$  stands for the time in 24-h format ( $j = 6, 7, 8, \dots, 18$ ),  $RSPF$  stands for the rooftop solar PV footprint of a given building ( $m^2$ ),  $EC$  stands for the total electricity consumption of a given building (kWh), and  $RA$  stands for the total rooftop area of a given building ( $m^2$ ).

By multiplying (i) the total solar radiation at a certain time frame (e.g., 6 a.m. to 7 a.m.) for an entire month, (ii) the available rooftop area at a certain time frame in month  $i$ , and (iii) the solar PV module efficiency, it is possible to calculate the rooftop solar PV potential of month  $i$  at a certain time frame. This process can be continued for every time frame and every month for calculating the rooftop solar PV potential of a year.

By dividing (i) the total electricity consumption by (ii) the rooftop solar PV potential per unit rooftop area of a given building, it is possible to calculate the total rooftop area required for a given building to meet its electricity demand. This process can be done for the entire buildings in the neighborhood for calculating the rooftop solar PV footprint of that geographical boundary.

## 36.4 Results and Discussions

To actually calculate and analyze the rooftop solar PV footprint by applying the proposed framework, this study conducted a case study for buildings in Yeoksam-dong and Samseong-dong in the Gangnam District, Seoul, South Korea. Yeoksam-dong and Samseong-dong are wards of the Gangnam District with 4933 and 2500 buildings, respectively. Teheranno, a street in the Gangnam district, runs through Yeoksam-dong and Samseong-dong, which holds most of the tallest buildings in Seoul [16].

First, to calculate the available rooftop area solar PV footprint in Yeoksam-dong and Samseong-dong, this study conducted the Hillshade analysis for 12 days (on the fifteenth of each month from January to December) at hourly intervals (from 6 a.m. to 6 p.m.), resulting in a total of 156 times. Second, to calculate the rooftop solar PV potential in Yeoksam-dong and Samseong-dong, this study used 15% and 18% for the minimum and maximum solar PV module efficiency, respectively. Third, to calculate the rooftop solar PV footprint in Yeoksam-dong and Samseong-dong, this study conducted data matching between the calculated rooftop solar PV potential and collected energy consumption data of each building using the official building address. As a result, the rooftop solar PV footprint in Yeoksam-dong and Samseong-dong was calculated for 2531 and 1255 buildings from a total of 4933 and 2500 buildings, respectively.

As shown in Table 36.1, the rooftop solar PV potential and footprint in Yeoksam-dong were calculated and compared with the building electricity consumption and total rooftop area, respectively. First, the rooftop solar PV potential was examined to consider the building electricity supply and demand separately and to analyze the energy usage aspect. From the perspective of building electricity supply, the rooftop solar PV potential was examined. When the solar PV module efficiency is 15%, the total rooftop solar PV potential in Yeoksam-dong came out to be 105,956 MWh, whereas it came out to be 127,147 MWh when the solar PV module efficiency is 18%. From the perspective of building electricity demand, the building electricity consumption was examined. The total electricity consumption of 2531 buildings in Yeoksam-dong was found to be 815,955 MWh. According to aforementioned building electricity supply and demand in Yeoksam-dong, it was shown that the

**Table 36.1** The rooftop solar PV potential and footprint results in Yeoksam-dong by solar PV module efficiency

Solar PV module efficiency	15%	18%
No. of buildings	2531	
Total electricity consumption (MWh)	815,955	
Rooftop solar PV potential (MWh)	105,956	127,147
Self-sufficiency rate (%)	12.99	15.58
Total rooftop area (m <sup>2</sup> )	757,703	
Rooftop solar PV footprint (m <sup>2</sup> )	5,561,714	4,634,762
Solar PV occupancy rate (%)	734.02	611.69

self-sufficiency rate could reach 12.99% and 15.58% when the solar PV module efficiency is 15% and 18%, respectively.

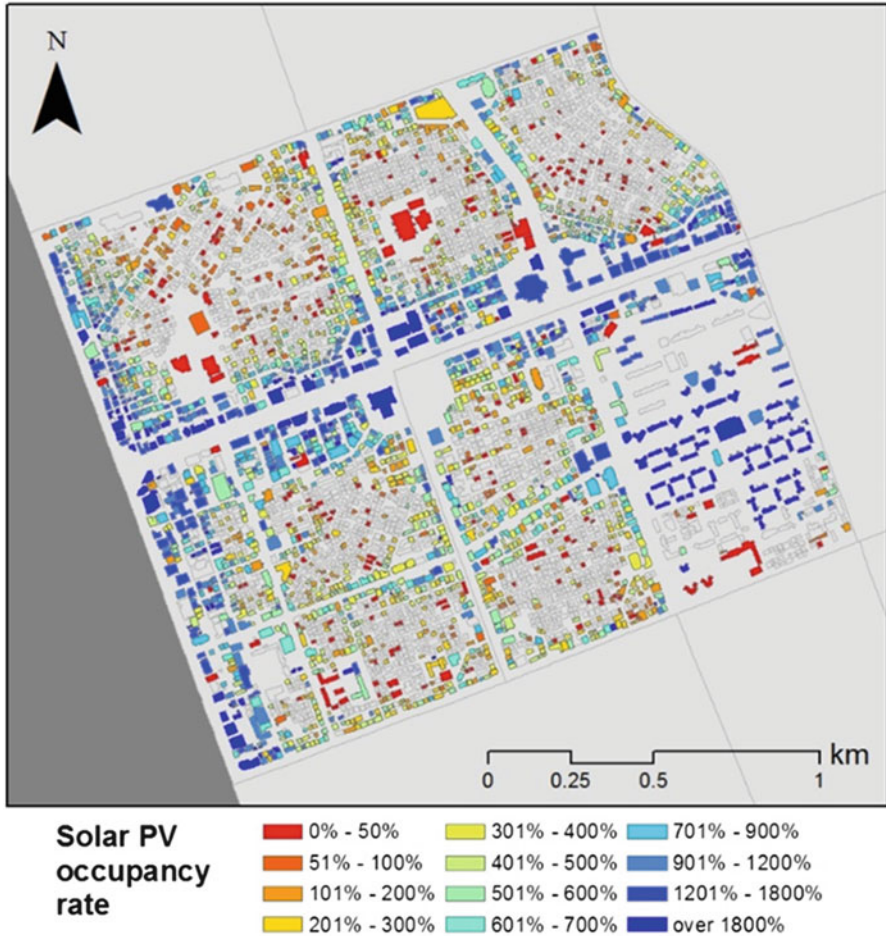
Second, the rooftop solar PV footprint was examined to consider and analyze both building electricity supply and demand at the same time and to analyze the rooftop usage aspect. When the solar PV module efficiency is 15%, the total rooftop solar PV footprint in Yeoksam-dong came out to be 5,561,714 m<sup>2</sup>, whereas it came out to be 4,634,762 m<sup>2</sup> when the solar PV module efficiency is 18%. That is, 5,561,714 m<sup>2</sup> and 4,634,762 m<sup>2</sup> of rooftop area is required for installing DSG to supply the amount of electricity consumed in 2531 buildings in Yeoksam-dong, when the solar PV module efficiency is 15% and 18%, respectively. This information on the rooftop solar PV footprint can be used to directly plan how much rooftops should be utilized for installing DSG from the urban level. However, the total rooftop area of 2531 buildings in Yeoksam-dong was found to be 757,703 m<sup>2</sup>, which is far less than its rooftop solar PV footprint. This indicates that it is not enough to offset the total electricity consumption even if all the rooftops of 2531 buildings in Yeoksam-dong are used for installing DSG. To be 100% self-sufficient in electricity, 734.02% and 611.69% of the total rooftop area are required for the 2531 buildings in Yeoksam-dong, when the solar PV module efficiency is 15% and 18%, respectively.

Figures 36.2 and 36.3 show the solar PV occupancy rate of the individual building in Yeoksam-dong when the solar PV module efficiency is 15% and 18%, respectively. As shown in Fig. 36.2, among a total of 2531 buildings, 247 buildings (i.e., colored in red in Fig. 36.2) and 120 buildings (i.e., colored in orange in Fig. 36.2), respectively, require less than 50% and 100% of their own rooftop areas to offset the electricity consumption with DSG, when the solar PV module efficiency is 15%. That is, only 367 buildings (i.e., 14.5% of total buildings) are eligible for being 100% self-sufficient in electricity in Yeoksam-dong when DSG is installed on their rooftop with 15% module efficiency.

Meanwhile, as shown in Fig. 36.3, among a total of 2531 buildings, 272 buildings (i.e., colored in red in Fig. 36.3) and 129 buildings (i.e., colored in orange in Fig. 36.3), respectively, require less than 50% and 100% of their rooftop areas to offset the electricity consumption with DSG, when the solar PV module efficiency is 18%. That is, still only 401 buildings (i.e., 15.8% of total buildings) are eligible for being 100% self-sufficient in electricity in Yeoksam-dong when DSG is installed on their rooftop with 18% module efficiency.

As shown in Table 36.2, the rooftop solar PV potential and footprint in Samseong-dong was calculated and compared with the building electricity consumption and total rooftop area, respectively. First, the rooftop solar PV potential was examined to consider the building electricity supply and demand separately and to analyze the energy usage aspect. From the perspective of building electricity supply, the rooftop solar PV potential was examined. When the solar PV module efficiency is 15%, the total rooftop solar PV potential in Samseong-dong came out to be 75,590 MWh, whereas it came out to be 90,709 MWh when the solar PV module efficiency is 18%. From the perspective of building electricity demand, the building electricity consumption was examined. The total electricity consumption of 1255



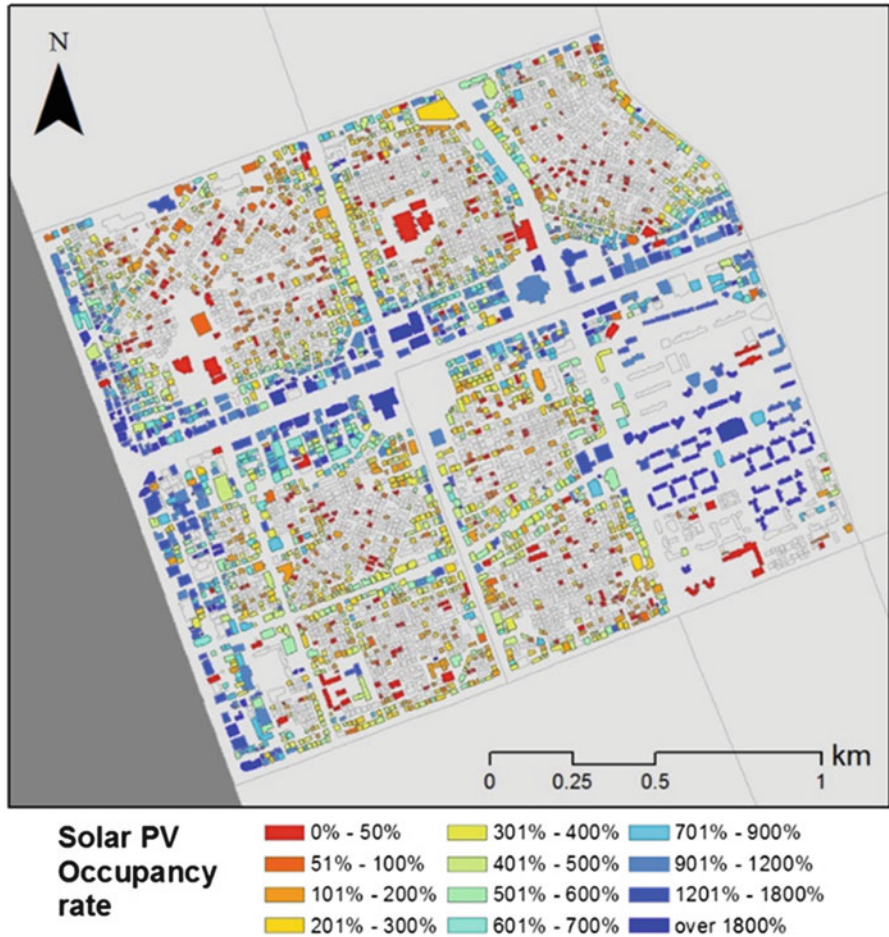


**Fig. 36.2** The solar PV occupancy rate of the individual building in Yeoksam-dong (module efficiency: 15%)

buildings in Samseong-dong was found to be 531,887 MWh. According to aforementioned building electricity supply and demand in Samseong-dong, it was shown that the self-sufficiency rate could reach 14.21% and 17.05% when the solar PV module efficiency is 15% and 18%, respectively.

Second, the rooftop solar PV footprint was examined to consider and analyze both building electricity supply and demand at the same time and to analyze the rooftop usage aspect. When the solar PV module efficiency is 15%, the total rooftop solar PV footprint in Samseong-dong came out to be 4,568,403 m<sup>2</sup>, whereas it came out to be 3,807,003 m<sup>2</sup> when the solar PV module efficiency is 18%. That is, 4,568,403 m<sup>2</sup> and 3,807,003 m<sup>2</sup> of rooftop area is required for installing DSG to supply the amount of electricity consumed in 1255 buildings in Samseong-dong,

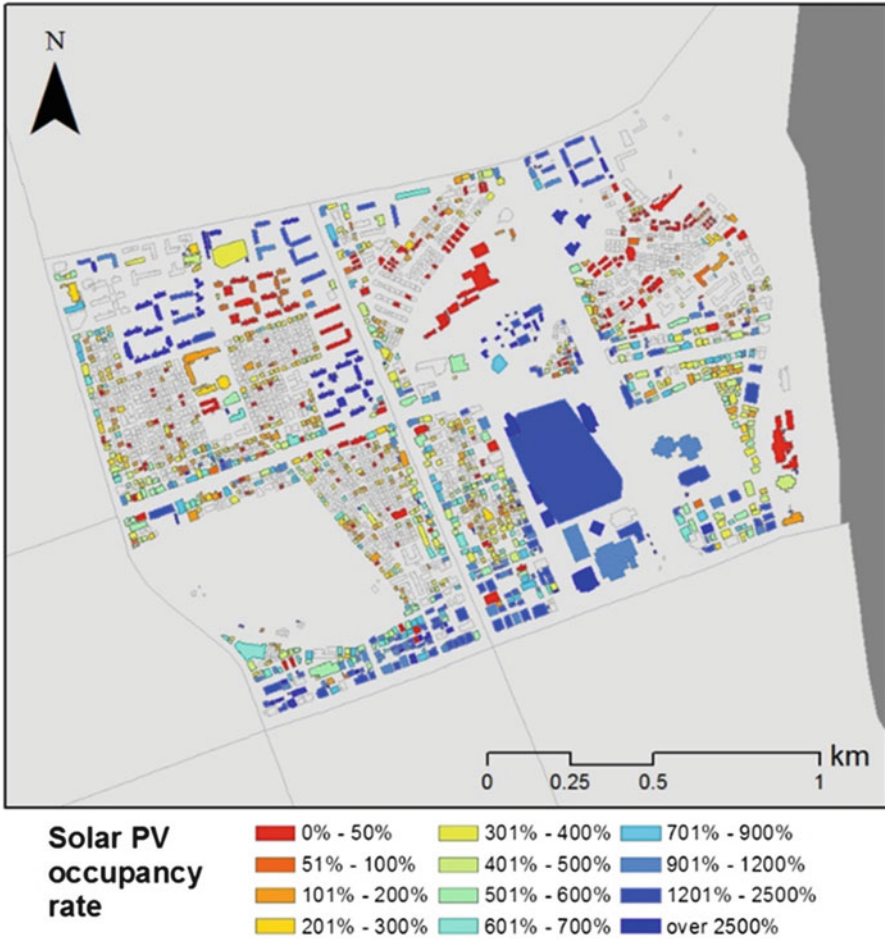




**Fig. 36.3** The solar PV occupancy rate of the individual building in Yeoksam-dong (module efficiency: 18%)

**Table 36.2** The rooftop solar PV potential and footprint results in Samseong-dong by solar PV module efficiency

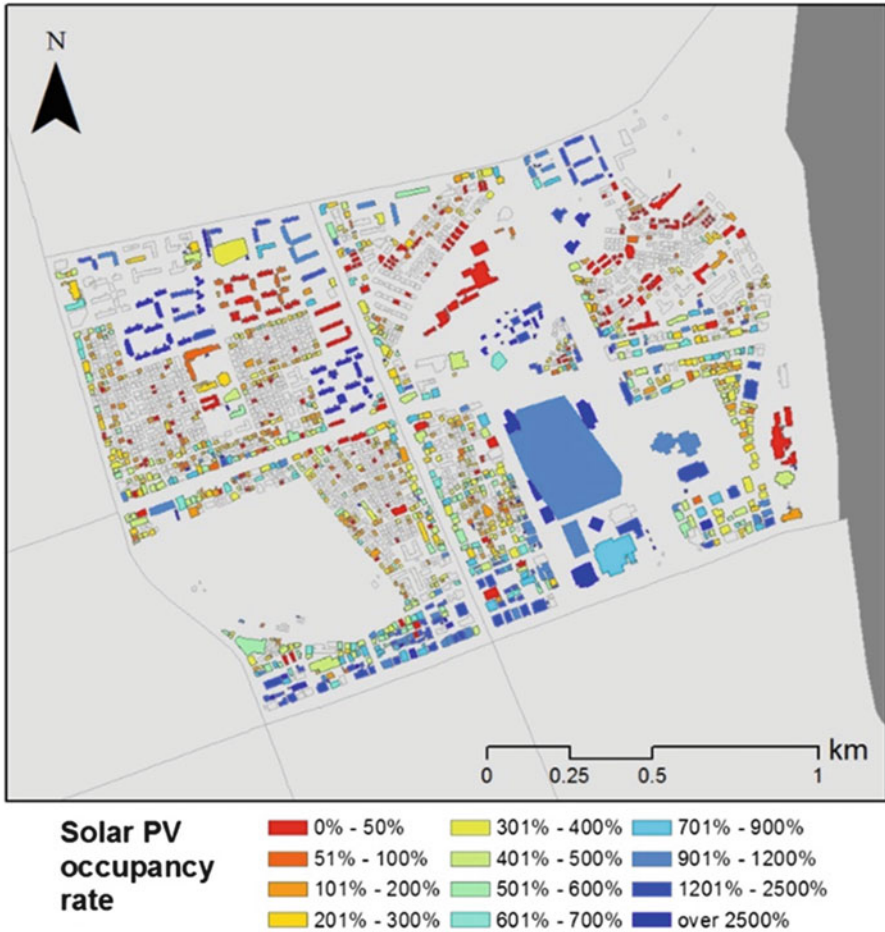
Solar PV module efficiency	15%	18%
No. of buildings	1255	
Total electricity consumption (MWh)	531,887	
Rooftop solar PV potential (MWh)	75,590	90,709
Self-sufficiency rate (%)	14.21	17.05
Total rooftop area (m <sup>2</sup> )	522,802	
Rooftop solar PV footprint (m <sup>2</sup> )	4,568,403	3,807,003
Solar PV occupancy rate (%)	873.83	728.19



**Fig. 36.4** The solar PV occupancy rate of the individual building in Samseong-dong (module efficiency: 15%)

when the solar PV module efficiency is 15% and 18%, respectively. However, the total rooftop area of 1255 buildings in Samseong-dong was found to be 522,802 m<sup>2</sup>, which is far less than its rooftop solar PV footprint. This indicates that it is not enough to offset the total electricity consumption even if all the rooftops of 1255 buildings in Samseong-dong are used for installing DSG. To be 100% self-sufficient in electricity, 873.83% and 728.19% of the total rooftop area are required for the 1255 buildings in Samseong-dong, when the solar PV module efficiency is 15% and 18%, respectively.

Figures 36.4 and 36.5 show the solar PV occupancy rate of the individual building in Samseong-dong when the solar PV module efficiency is 15% and 18%, respectively. As shown in Fig. 36.4, among a total of 1255 buildings,



**Fig. 36.5** The solar PV occupancy rate of the individual building in Samseong-dong (module efficiency: 18%)

172 buildings (i.e., colored in red in Fig. 36.4) and 50 buildings (i.e., colored in orange in Fig. 36.4), respectively, require less than 50% and 100% of their own rooftop areas to offset the electricity consumption with DSG, when the solar PV module efficiency is 15%. That is, only 222 buildings (i.e., 17.7% of total buildings) are eligible for being 100% self-sufficient in electricity in Samseong-dong when DSG is installed on their rooftop with 15% module efficiency.

Meanwhile, as shown in Fig. 36.5, among a total of 1255 buildings, 176 buildings (i.e., colored in red in Fig. 36.5) and 69 buildings (i.e., colored in orange in Fig. 36.5), respectively, require less than 50% and 100% of their rooftop areas to offset the electricity consumption with DSG, when the solar PV module efficiency is 18%. That is, still only 245 buildings (i.e., 19.5% of total buildings) are eligible for

being 100% self-sufficient in electricity in Samseong-dong when DSG is installed on their rooftop with 18% module efficiency.

## 36.5 Conclusions

This study proposed a framework for calculating the rooftop solar PV footprint considering building electricity supply and demand from the urban level. Toward this end, this study suggested a novel method for calculating the available rooftop area, rooftop solar PV potential, and rooftop solar PV footprint using data on building information, solar radiation, and energy consumption. To apply the proposed framework to a real example, a case study was conducted for buildings in Yeoksam-dong and Samseong-dong in the Gangnam District, Seoul, South Korea. As a result, the rooftop solar PV potential and footprint in Yeoksam-dong and Samseong-dong was calculated and compared.

In terms of the energy usage aspect, the self-sufficiency rate of 1255 buildings in Samseong-dong (i.e., up to 17.05% with 18% module efficiency) was superior to that of 2531 buildings in Yeoksam-dong (i.e., up to 15.58% with 18% module efficiency).

In terms of the rooftop usage aspect, the solar PV occupancy rate of 2531 buildings in Yeoksam-dong (i.e., at least 611.69% with 18% module efficiency) was superior to that of 1255 buildings in Samseong-dong (i.e., at least 728.19% with 18% module efficiency). That is, Yeoksam-dong requires less rooftop area than Samseong-dong for installing DSG to become 100% self-sufficient in electricity, which indicates that Yeoksam-dong could be more effective in utilizing the rooftop area for installing DSG.

The results of this study show that the energy and rooftop usage performance could differ from each other. Thus, it is important to consider both the self-sufficiency rate and rooftop solar PV footprint when evaluating the building energy performance considering electricity supply and demand from the urban-level.

### Nomenclature

DSG	Distributed solar generation
E-AIS	Electronic Architectural administration Information System
ESRI	Environmental Systems Research Institute
GIS	Geographical information system
KASI	Korea Astronomy and Space Science Institute
KNREC	Korea New and Renewable Energy Center
MOLIT	Ministry of Land, Infrastructure, and Transport
nZEB	Nearly zero-energy building
PV	Photovoltaic
SPACEN	Spatial Information Industry Promotion Institute
WRDC	World Radiation Data Centre

**Acknowledgments** This research was supported by a grant (16CTAP-C117226-01) from the Technology Advancement Research Program (TARP) funded by the Ministry of Land, Infrastructure, and Transport of Korean government.

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