Framework for the analysis of the potential of the rooftop photovoltaic system to achieve the net-zero energy solar buildings

Choongwan Koo¹, Taehoon Hong¹*, Hyo Seon Park¹ and Gangcheol Yun²

¹ Department of Architectural Engineering, Yonsei University, Seoul 120-749, Republic of Korea
² Strategic Planning Team, Parsons Brinckerhoff, Seoul 135-763, Republic of Korea

ABSTRACT

New renewable energy is attracting considerable attention as a future energy source. The photovoltaic (PV) market, in particular, has grown significantly during the past decade. The use of the rooftop PV system in buildings in urban environments is being actively promoted. This research was conducted to develop a framework for the analysis of the potential of the rooftop PV system to achieve the net-zero energy solar buildings in terms of energy supply. To verify the feasibility of the proposed framework, a total of 5418 elementary school facilities located in 16 administrative divisions in South Korea were selected as case studies. This research (i) collected information on the elementary school facilities, the rooftop PV system, and the meteorological and geographical characteristics by region; (ii) conducted an energy supply analysis by applying the rooftop PV system; (iii) conducted an energy demand analysis; (iv) analyzed the energy substitution effect; (v) presented the current status of the energy supply and demand in each region using the geographical information system; (vi) analyzed the causal relationship between the energy supply and demand by region; and (vii) proposed an energy supply and demand strategy by region. This research can help elementary school facility managers or policymakers conduct an energy supply and demand analysis as well as propose an energy supply and demand strategy. It can be used as part of an educational facility improvement program. The framework proposed in this research can also be applied to any other country or sector in the global environment. © 2013 The Authors. Progress in Photovoltaics: Research and Applications published by John Wiley Ltd.

KEYWORDS
zero energy building; rooftop photovoltaic system; carbon neutral school; energy supply and demand; geographical information system

*Correspondence
Taehoon Hong, Yonsei University, 262 Seongsanno, Seodaemun-gu, Seoul, 120-749, Republic of Korea.
E-mail: hong7@yonsei.ac.kr

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1. INTRODUCTION

1.1. Research background and objective

Since the start of the Industrial Revolution in the mid-18th century, the use of fossil fuels has drastically increased, and the rise in the emission of greenhouse gases (GHGs) due to the increased use of fossil fuels has caused global warming. To cope with today’s global climate change issues, leading countries ratified the United Nations Framework Convention on Climate Change in Rio de Janeiro, Brazil in June 1992. At the third Conference of the Parties held in Kyoto, Japan on 11 December 1997, the so-called Kyoto Protocol, which defined the obligatory GHG emissions reduction for industrialized countries, was first adopted [1,2].

The US and the EU countries, which represent the countries that adopted the GHG emissions reduction obligation, are believed to consume about 40% of the total fossil fuels in the building sector worldwide. Thus, they are considered as the main contributors to global GHG emissions [3–6]. Under this background, many countries have shown growing interest in zero energy buildings (ZEBs), which are considered as the means of reducing dependence on fossil fuels.
and GHG emissions. The EU approved the Energy Performance of Buildings Directive on 16 December 2002 to strengthen its control of the total energy consumption in building sector, while the UK announced in December 2006 that by 2016, all new homes in England would be ZEBs [7–11]. The US Department of Energy supports research on ZEBs, and its key research organizations are (i) the National Renewable Energy Laboratory, (ii) the Florida Solar Energy Center, (iii) the Lawrence Berkeley National Laboratory, and the Oak Ridge National Laboratory. From 2008, Department of Energy has funded these organizations with 40 million $US, in the hope that about 50–70% of energy consumption in existing houses would be saved [12–14]. Also, various countries are either enacting or reforming their building laws related to energy efficiency. Ultimately, they are planning to realize ZEBs to improve the energy performance of buildings [15–20].

There is growing interest in new renewable energy (NRE) and particularly, in the expansion of the photovoltaic (PV) market, to realize ZEBs [21–30]. Moreover, the introduction of the rooftop PV system in urban regions using the rooftop area of a building is being actively promoted. Each government is promoting financial support systems such as feed-in tariffs, renewable portfolio standards, tax credits, or subsidies, depending on the country’s circumstances, in order to grow the PV market [31–39]. To establish a successful long-term strategy in support of such government policy, the potential of the energy supply and demand should be analyzed. Also, reflecting the results of such analyses, the budget for the government’s financial support system should be clearly delimited to make the aforementioned policy sustainable. Thus, this study was conducted to develop a framework for the analysis of the potential of the rooftop PV system to achieve ZEBs in terms of energy supply. In addition, a visual map of the regional energy supply and demand was developed using GIS, which is the newest technology for making better decisions about location. Such a correct decision about location is a key factor for the success of the introduction of the rooftop PV system. The developed framework can be applied to any other country’s facilities in terms of their global environmental impact.

1.2. Research scope and method

According to previous studies, it was shown that various factors (such as the units of the balance, the type of energy use, the type of renewable energy source, the type of building, different climate, and both for on-grid and off-grid) should be considered in the ZEBs definition [8,12–14,17,40–46]. As mentioned previously, this study aimed to analyze the potential of the rooftop PV system to achieve ZEBs. Thus, this study clearly defined the buildings utilizing PV technologies as net-zero energy solar buildings (nZESBs), in which no fossil fuels are consumed, and the annual electricity consumption equals annual electricity generation.

To verify the proposed framework, 5418 elementary schools located in 16 administrative divisions in South Korea were analyzed [47]. These elementary schools were selected based on several considerations. (i) Generally, the smaller the floor area ratio is, the smaller the energy demand per rooftop area becomes, so the greater the energy substitution effect of the implementation of the rooftop PV system would be. Since the floor area ratio of educational facilities is smaller than that of multi-family housing facilities or office buildings, it was determined that the energy substitution effect of the implementation of the rooftop PV system in educational facilities would be considerable. (ii) To verify the proposed framework, a facility type that is evenly distributed nationwide, is abundant in number, and has high energy consumption was selected. Among educational facilities, elementary school facilities were determined to be appropriate for a case study (refer to Table S1 of Supporting Information).

Meanwhile, the results of this study can be used in a preliminary feasibility study for the introduction of the rooftop PV system from the macroscopic view. Thus, it was determined that the averaging approach was appropriate for achieving the objective of this study. The averaging approach was frequently used in previous studies to estimate the solar radiation, which affected the electricity generation of the PV system [48–52].

The proposed framework was developed in seven steps: (i) data collection; (ii) analysis of the energy supply by the rooftop PV system; (iii) analysis of the energy demand; (iv) analysis of the energy substitution effect; (v) geographical analysis of the regional energy supply and demand; (vi) statistical correlation analysis of the regional energy supply and demand; and (vii) establishment of the regional energy supply and demand strategy.

1.3. Literature reviews

Various studies have analyzed the potential of the rooftop PV system [53–68]. Wiginton et al. [53] calculated the rooftop solar PV potential by estimating the approximately available rooftop area per population in southeastern Ontario in Canada. Yue and Huang [54] estimated the overall solar PV potential by building type based on the land use zoning in Tainan City and Tainan County in Taiwan. Ordóñez et al. [55] estimated the solar PV potential by identifying representative samples from the residential buildings in Andalusia, Spain, using an urban map acquired from Google Earth™. Izquierdo et al. [56] proposed a method of estimating the available rooftop area in existing buildings using the representative stratified-sampling on vectorial geographical information system (GIS) maps in urban areas. Furthermore, Izquierdo et al. [57] estimated the rooftop solar PV potential in Spain through representative stratified-sampling and conducted an economic analysis. Süri et al. [58] approximated the residential areas in EU member states and candidate countries using the CORINE Land Cover (CLC90) database. From the results, they calculated the solar PV potential by region and country. Hofierka and Kaňuk [59] estimated the solar PV potential in the building rooftop area in urban areas of Bardejov, a small
city in eastern Slovakia, using open-source solar radiation tools.

However, there are several limitations in the previous research: (i) the rooftop area was merely estimated using the sample data. To establish national and regional policies, more concrete analysis results are required; (ii) the impact factors (e.g., solar radiation, and the installation angle and orientation of the PV system) were partially considered; (iii) the analysis of the energy supply by the rooftop PV system was conducted, but the analysis of the energy demand was not conducted. Accordingly, a sufficient foundation for establishing the legal and financial support policies was not provided; (iv) though some of the studies mapped the rooftop solar PV potential using GIS, most of them merely showed the numerical analysis results without the intuitive analysis; and (v) the comprehensive and nationwide analysis of one building type was not conducted, and thus more concrete policies or strategies could not be established. This study aimed to solve these limitations.

2. FRAMEWORK FOR THE ANALYSIS OF THE POTENTIAL OF THE ROOFTOP PHOTOVOLTAIC SYSTEM TO ACHIEVE THE NET-ZERO ENERGY SOLAR BUILDINGS

This study proposes a framework for the analysis of the potential of the rooftop PV system to achieve the nZESBs through a comprehensive seven-stage process. To verify the feasibility of the proposed framework, an elementary school facility was used as a case study.

As shown in Figure 1, physical, utilization, and geographic information on the target elementary school facility was initially collected. Physical information on the rooftop PV system and regional meteorological and geographic information were also collected. Second, the electricity generation per rooftop area—the energy supply—through the implementation of the rooftop PV system by elementary school facility was analyzed. Third, the energy demand, including the energy consumption per rooftop area, the number of persons per rooftop area, and the number of classes per rooftop area by elementary school facility, was analyzed. Fourth, the energy substitution effect was analyzed using the results of the analysis of the regional energy supply and demand by elementary school facility. Fifth, a visual map of the current regional energy supply and demand by elementary school facility through the implementation of the rooftop PV system was provided using GIS, from the geographic perspective. Sixth, a statistical correlation analysis was conducted to determine the causal relationship between the regional energy supply and demand by elementary school facility. Finally, a regional energy supply and demand strategy was provided based on the results of the analysis of the regional energy supply and demand by elementary school facility.

3. A CASE STUDY FOR THE VALIDATION OF THE PROPOSED FRAMEWORK

3.1. Step 1: Data collection

Data were collected to analyze the potential of the rooftop PV system and of the energy supply and demand by elementary school facility. As shown in Table 1, physical, utilization, and geographic information on the target elementary school facility was first collected [47,69]. Second, physical information on the rooftop PV system such as the capacity, efficiency, miscellaneous losses, width, and length were collected. Third, for the regions where the rooftop PV system would be installed, regional meteorological information including the monthly average daily solar radiation and the monthly average temperature, and regional geographical information such as the latitude and the meridian altitude at noon of winter solstice were collected [70–73]. The time scope of the data collection was set at the year 2010 because in that year, all the aforementioned information could be accessed.

The physical information on an elementary school facility includes its total floor, building, and rooftop areas; while its utilization information includes its electricity consumption, number of persons, and number of classes. Its geographic information includes its administrative divisions, address, latitude, and longitude. As shown in Table S1 (Supporting Information), the 16 administrative divisions in South Korea have a total of 6249 elementary school facilities. To ensure the feasibility of the results in the next process, the data were sorted out according to the following criteria. (i) If the data had a missing value in either the physical or the utilization information, the data was excluded from the database. (ii) If the energy consumption per unit area was in the top or bottom 5%, it was considered an outlier and was excluded from the database. (Here, the energy consumption per unit area was calculated based on the rooftop area because this study aimed to analyze the potential of the rooftop PV system in terms of the energy supply.) Based on these two criteria, a total of 5418 elementary school facilities were finally selected for the database.

Next, physical information on the rooftop PV system including the capacity, efficiency, miscellaneous losses, width, and length of the solar PV panel were collected. The International Renewable Energy Agency (IRENA) [11] provided the efficiency and price projections on a multi-crystalline silicon PV system from 2010 to 2015 (Table S2 of Supporting Information). Based on the International Renewable Energy Agency [11], the specifications of the PV panel and inverter were determined (Table S3 of Supporting Information).

To analyze the energy supply by elementary school facility for the regions where the rooftop PV system would be installed, regional meteorological information such as the monthly average daily solar radiation and the monthly average temperature as well as the regional geographical
information including the latitude and the meridian altitude at noon of winter solstice were collected. As the 16 administrative divisions in South Korea were targeted, the meteorological and geographic information collected was limited to them. Table S4 (Supporting Information) shows the monthly average daily solar radiations by region in 2010, which were collected from the New and Renewable Energy Data Center [70]. For the regions among the 16 administrative divisions where the monthly average daily solar radiation was not measured, the measured data from the geographically closest region was used. Table S5 (Supporting Information) shows the monthly average temperatures in 2010 as collected by Korea Meteorological Administration [71,72]. Table S6 (Supporting Information) shows the latitudes of the 16 administrative divisions in South Korea, which were collected from the geographical information offered by Google Earth™. The meridian altitude at noon of winter solstice by region was calculated using Equation (1).

\[ \tau = 90^\circ - \phi - \varepsilon \]

where \( \tau \) is the minimum incidence angle of the sun (the meridian altitude at noon of winter solstice by region), \( \phi \) is the regional latitude, and \( \varepsilon \) is the tilt angle of the Earth’s axis (23.5°).
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Table I. Basic information for the analysis of the potential of the rooftop photovoltaic system.

| Main classification                                             | Sub classification | Detailed description |
|-----------------------------------------------------------------|-------------------|---------------------|
| Physical information of the building                            | Total floor area   | (1) m²              |
|                                                                 | Building area      | (1) m²              |
|                                                                 | Rooftop area       | (1) m²              |
| Utilization information on the building                         | Electricity consumption | (1) kWh           |
|                                                                 | The number of persons | (1) person        |
|                                                                 | The number of classes | (1) class          |
| Geographical information on the building                        | Administrative division | (1) city or province |
|                                                                 | Address            | ()                  |
|                                                                 | Latitude           | (1) °N              |
|                                                                 | Longitude          | (1) °E              |
| Physical information on the solar photovoltaic panel            | Capacity           | (1) W               |
|                                                                 | Efficiency         | (1) %               |
|                                                                 | Miscellaneous losses | (1) %               |
|                                                                 | Width              | (1) mm              |
|                                                                 | Length             | (1) mm              |
| Regional meteorological information                             | Monthly average daily solar radiation | (1) kWh/m²/day |
| Regional geographical information                               | Monthly average temperature | (1) °C           |
|                                                                 | Latitude           | (1) °N              |
|                                                                 | Meridian altitude at noon of winter solstice | (1) °       |

3.2. Step 2: Analysis of the energy supply through the application of the rooftop photovoltaic system

3.2.1. Main considerations for analyzing the energy supply.

As shown in Step 1, the physical information of the elementary school facilities, the physical information of the rooftop PV system, and the regional meteorological and geographic information were collected (Tables S4–S6 of Supporting Information). These factors directly affect the electricity generation efficiency of the rooftop PV system [74–77].

First, the available rooftop area where the rooftop PV system can be installed must be calculated to analyze the energy supply. GRI [78] analyzed the available rooftop area by building type in South Korea and showed that the available rooftop area in educational facilities averaged 61.2% per building area (maximum of 92.5% and minimum of 37.3%). Based on this, 61.2% (α) was used as the ratio of rooftop area to building area for calculating the available rooftop area in elementary school facilities (Table S7 of Supporting Information).

Second, the physical characteristics of the solar PV panel affect its electricity generation. The capacity, efficiency, miscellaneous losses, width, and length of the solar PV panel directly affect its electricity generation (Table S3 of Supporting Information).

Third, the meteorological information in the region where the rooftop PV system will be installed directly affects the electricity generation of the rooftop PV system. For example, the monthly average daily solar radiation and the monthly average temperature, as well as the latitude and the meridian altitude of the PV system installation region where the target elementary school facility is located, are very important factors (Tables S4–S6 of Supporting Information).

Finally, using the aforementioned information, the number of panels installed in the rooftop PV system can be calculated, which is directly linked to their electricity generation. As shown in Figure S1 (Supporting Information), the installation area including the shaded area of a PV panel can be calculated.

3.2.2. Analysis of the optimal installation angle using the genetic algorithm.

Table II shows the results of the analysis of the optimal installation angle and the electricity generation of the rooftop PV system by region in various indices. To derive such optimization results, the following criteria were established. (i) The optimization goal was set at the savings-to-investment ratio (SIR). As an index of the relative value, SIR can be calculated as the benefit-to-cost ratio converted into the present worth from the perspective of the life cycle (Equation (2)). If SIR > 0, the introduction of the rooftop PV system is deemed feasible and the break-even point is determined to have been reached. Meanwhile, as shown in Table S8 (Supporting Information), the key elements of the life cycle cost and life cycle CO₂ analyses were assumed [79–85]; (ii) the average rooftop area of the elementary school facility was set at the available rooftop area (third column (A) of Table II); (iii) the specifications shown in Table S3 (Supporting Information) were used in the rooftop PV system. Particularly, the width (1460 mm) and the length (980 mm) were used as the basic elements of the calculation of the installation area (the equation shown in Figure S1 (Supporting Information) was used to calculate the installation area); (iv) the information shown in Tables S4–S6 (Supporting Information) was used for the regional meteorological information such as the monthly average daily solar radiation and the monthly average temperature, and for the regional
| No. | Region         | Regional average rooftop area (m²) | Optimal slope of panel (°) | Installation area per unit (m²/unit) | No. of panels (EA) | Total installation areas (m²) | Total electricity generation (kWh) | Electricity generation per unit (kWh/unit) | Electricity generation per unit area (kWh/m²) | Saving-to-investment ratio (%) |
|-----|----------------|------------------------------------|---------------------------|-------------------------------------|-------------------|-------------------------------|-------------------------------------|------------------------------------------|---------------------------------------------|-------------------------------|
| 1   | Seoul          | 1510.4                             | 34.397                    | 2.627                               | 574               | 1507.83                       | 136874                              | 238.46                                   | 90.78                                        | 2.291                         |
| 2   | Busan          | 1298.4                             | 32.110                    | 2.458                               | 528               | 1297.76                       | 143361                              | 271.52                                   | 110.47                                       | 2.610                         |
| 3   | Daegu          | 1436.9                             | 33.116                    | 2.500                               | 574               | 1435.22                       | 145830                              | 254.06                                   | 101.61                                       | 2.443                         |
| 4   | Incheon        | 1396.9                             | 33.492                    | 2.605                               | 536               | 1396.18                       | 134948                              | 251.77                                   | 96.66                                        | 2.418                         |
| 5   | Gwangju        | 1648.3                             | 30.686                    | 2.426                               | 679               | 1647.40                       | 169250                              | 249.26                                   | 102.74                                       | 2.393                         |
| 6   | Daegu          | 1590.6                             | 32.587                    | 2.524                               | 630               | 1590.30                       | 164300                              | 260.79                                   | 103.31                                       | 2.505                         |
| 7   | Ulsan          | 1647.6                             | 32.082                    | 2.468                               | 667               | 1646.23                       | 184810                              | 277.08                                   | 112.26                                       | 2.663                         |
| 8   | Gyeonggi       | 1271.1                             | 33.264                    | 2.592                               | 490               | 1270.07                       | 119809                              | 244.51                                   | 94.33                                        | 2.349                         |
| 9   | Gangwon        | 1064.9                             | 34.584                    | 2.640                               | 403               | 1063.97                       | 102683                              | 254.80                                   | 96.51                                        | 2.449                         |
| 10  | Chungcheongbuk | 1250.5                             | 29.950                    | 2.471                               | 505               | 1247.86                       | 119204                              | 235.58                                   | 95.34                                        | 2.260                         |
| 11  | Chungcheongnam | 1208.9                             | 32.171                    | 2.529                               | 478               | 1208.63                       | 121240                              | 253.64                                   | 100.31                                       | 2.436                         |
| 12  | Jeollabuk      | 1240.2                             | 30.489                    | 2.441                               | 508               | 1239.85                       | 125130                              | 246.32                                   | 100.92                                       | 2.365                         |
| 13  | Jeollanam      | 1256.1                             | 28.496                    | 2.349                               | 534               | 1254.39                       | 137125                              | 256.79                                   | 109.32                                       | 2.461                         |
| 14  | Gyeongsangbuk  | 1104.6                             | 34.051                    | 2.564                               | 431               | 1104.93                       | 115268                              | 268.07                                   | 104.56                                       | 2.579                         |
| 15  | Gyeongsangnam  | 1320.4                             | 33.790                    | 2.493                               | 529               | 1318.66                       | 147891                              | 279.57                                   | 112.15                                       | 2.687                         |
| 16  | Jeju           | 1285.1                             | 23.336                    | 2.180                               | 598               | 1283.76                       | 139781                              | 237.32                                   | 108.88                                       | 2.272                         |

In the previous research, the rooftop area (third column (A)) accounted for 61.2% of the building area (78).
geographic information such as the latitude and the meridian altitude at noon of winter solstice; (v) after having established the aforementioned criteria, a genetic algorithm was applied to derive the optimal slope of the rooftop PV system by using the software program called Evolver 5.5. Accordingly, the optimization process was established using a Microsoft-Excel-based Visual Basic for Applications as shown in Figure 2. The detailed information of the optimization process was presented in Table S9 (Supporting Information).

$$SIR = \frac{\sum_{t=0}^{n} BES_t + BET_t}{\sum_{t=0}^{n} CIt + CRrt + CRtt} (1 + r)^t$$

where $SIR$ is the saving-to-investment ratio; $BES_t$ is the benefit from energy savings in year $t$; $BET_t$ is the benefit from the emissions trading in year $t$; $CIt$ is the cost of the initial investment in year $t$; $CRrt$ is the cost of the repair work in year $t$; $CRtt$ is the cost of the replacement work in year $t$; $r$ is the real discount rate; and $n$ is the period of the life cycle analysis.

For example, in Seoul, the implementation of the aforementioned criteria resulted in the following data (Table II). First, the regional average rooftop area was 1510.4 m² (third column (A) of Table II). The optimal slope of the rooftop PV system was 34.397º (fourth column (B) of Table II), and the installation area per unit was 2.627 m² (fifth column (C) of Table II). If a total of 574 panels would be installed (sixth column (D) of Table II), the total installation area would be 1507.83 m² (seventh column (E) of Table II). In this case, the total electricity generation...
would be 136,874 kWh (eighth column (F) of Table II), the electricity generation per unit would be 238,46 kWh/unit (ninth column (G) of Table II), and the electricity generation per unit area would be 90.78 kWh/m² (10th column (H) of Table II). Ultimately, the SIR would be 2.291 (11th column (I) of Table II). Such results were based on the consideration of all the monthly average daily solar radiations in Table S4 (Supporting Information), monthly average temperatures in Table S5 (Supporting Information), and latitude and meridian altitudes at noon of the winter solstice in Table S6 (Supporting Information). Based on this, the optimal slope of the rooftop PV system in the 5418 elementary school facilities in the 16 administrative divisions in South Korea was analyzed.

3.2.3. Analysis of electricity generation using the software program called “RETScreen”.

The available rooftop area by elementary school facility was calculated by applying the ratio of the available rooftop area to the building area (α), which was 61.2%, as shown in Table S7 (Supporting Information), to a total of 5418 elementary school facilities in South Korea. By using the optimal slope of the rooftop PV system, as shown in Table II, the electricity generation of the rooftop PV system was analyzed. Toward this end, RETScreen, an NRE simulation program co-developed by the Department of Natural Resources of Canada and the United Nations Environment Programme, was used. Table III shows the statistical information on the analysis results of the regional energy supply of the 5418 elementary school facilities. For example, 418 of the elementary schools in Seoul were used in the analysis (second column (A) of Table III). The total floor area was 3,687,710 m² (third column (B) of Table III), and the building area was 1,031,624 m² (fourth column (C) of Table III). By applying 61.2% (α) to the building area, the rooftop area became 631,354 m² (fifth column (D) of Table III). The electricity generation from the calculated available rooftop area using the rooftop PV system was 52,080,730 kWh (eighth column (G) of Table III). Finally, the electricity generation per rooftop area was 82,490 kWh/m² (nine column (H) of Table III). Based on this, electricity generation using the rooftop PV system in the 5418 elementary school facilities in the 16 administrative divisions in South Korea was analyzed. The results, along with the results of the analysis of the energy demand in Step 3, will be used to analyze the energy substitution effect in Step 4.

3.3. Step 3: Analysis of energy demand

As shown in Step 1, the physical and utilization information of the elementary school facilities were collected (Table I). By using such information, energy consumption was analyzed based on the characteristics of the elementary school facilities in terms of energy demand.

First, in the 2011 Educational Statistical Yearbook, the physical and utilization information was collected from a total of 6249 elementary school facilities in the 16 administrative divisions in South Korea [47]. As shown in Step 1, the data were selected based on the two criteria to determine the feasibility of the energy demand analysis results. In this process, a total of 5418 elementary school facilities were selected.

Second, energy consumption must be converted into identical units to analyze the regional energy demand in elementary school facilities. This is because the physical sizes such as the total floor, building, and rooftop areas, as well as the utilization size such as the number of persons or classes, of elementary school facilities differ considerably. As shown in Step 2, this study was conducted to analyze the potential of the rooftop PV system in terms of energy supply. Thus, the energy consumption per rooftop area was adopted as the energy demand analysis criterion. Also, 61.2% (α) was used to calculate the rooftop area by elementary school facility as the ratio of the rooftop area to the building area [78].

Third, by using the preceding information, indices such as the number of persons per rooftop area, the number of classes per rooftop area, and the energy consumption per rooftop area by elementary school facility were calculated. Table III shows the statistical information on the analysis results of the regional energy demand of 5418 elementary school facilities. For example, among the elementary schools in Seoul, a total of 418 were used in the analysis (second column (A) of Table III). The total floor area was 3,687,710 m² (third column (B) of Table III), and the building area was 1,031,624 m² (fourth column (C) of Table III). By applying 61.2% (α) to the building area, the rooftop area became 631,354 m² (fifth column (D) of Table III). The number of persons was 422,709 (sixth column (E) of Table III); the number of classes, 14,554 (seventh column (F) of Table III); and electricity consumption, 129,200,946 kWh (10th column (I) of Table III). Finally, the number of persons per rooftop area (m²) was 0.7047 (11th column (J) of Table III); the number of classes per rooftop area (m²), 0.0244 (12th column (K) of Table III); and the electricity consumption per rooftop area, 213.376 kWh/m² (13th column (L) of Table III). Based on this, electricity consumption of the 5418 elementary school facilities in the 16 administrative divisions in South Korea was analyzed. The results, along with the results of the analysis of the energy supply in Step 2, will be used to analyze the energy substitution effect in Step 4.

3.4. Step 4: Analysis of the energy substitution effect

By using the regional energy supply and demand analysis by elementary school facility, the energy substitution effect was assessed. Table IV shows the statistical information on the analysis results of the energy substitution effect of the 5418 elementary school facilities. For example, a total of 418 elementary schools in Seoul were used in the analysis (third column (A) of Table IV). The results are as follows.
Table III. Analysis of the regional energy supply and demand.

| No | No. of schools | Total floor area (m$^2$) | Building area (m$^2$) | Rooftop area (m$^2$) | No. of persons | No. of classes | Electricity generation (kWh) | Electricity generation per rooftop area (kWh/m$^2$) | Electricity consumptions (kWh) | Person per rooftop area (Person/m$^2$) | Class per rooftop area (Classes/m$^2$) | Electricity consumption per rooftop area (kWh/m$^2$) | (A) (B) (C) (D) = (C)*α | (E) (F) (G) (H) = (G)/(D) | (I) (J) = (E)/(D) | (K) = (F)/(D) | (L) = (I)/(D) |
|----|----------------|--------------------------|----------------------|----------------------|----------------|----------------|-----------------------------|---------------------------------|-----------------------------|---------------------------------|---------------------------------|---------------------------------|--------------------------|------------------------|------------------------|------------------------|------------------------|
| 1  | 418            | 3687710                  | 1031624              | 631354               | 422709         | 14554         | 52080730                    | 82.490                          | 129200946                    | 0.7047                          | 0.0244                          | 213376                         | 0.0021                  | 2100870                | 0.0164                 | 166833                | 0.0183                 |
| 2  | 277            | 2177336                  | 587689               | 359666               | 193644         | 7137          | 37954070                    | 105.526                         | 57631629                      | 0.5477                          | 0.0207                          | 166833                         | 0.0170                  | 47631629               | 0.0110                 | 141905               | 0.0091                 |
| 3  | 204            | 1644704                  | 478969               | 293129               | 169767         | 5835          | 28120720                    | 95.930                          | 40027903                      | 0.6020                          | 0.0209                          | 141905                         | 0.0147                  | 30027903               | 0.0109                 | 141905               | 0.0091                 |
| 4  | 199            | 1527185                  | 454231               | 277989               | 162346         | 5815          | 24436200                    | 87.900                          | 5928036                       | 0.5510                          | 0.0203                          | 199326                         | 0.0149                  | 3928036                | 0.0109                 | 137218               | 0.0091                 |
| 5  | 136            | 1088498                  | 366296               | 224173               | 111968         | 3819          | 22030490                    | 98.275                          | 29695157                      | 0.5090                          | 0.0176                          | 137218                         | 0.0149                  | 29695157               | 0.0109                 | 137218               | 0.0091                 |
| 6  | 128            | 1079765                  | 332674               | 203596               | 102475         | 3500          | 19585250                    | 96.192                          | 28384036                      | 0.4988                          | 0.0174                          | 143914                         | 0.0149                  | 28384036               | 0.0109                 | 143914               | 0.0091                 |
| 7  | 114            | 909103                   | 306911               | 187830               | 80452          | 2783          | 20008200                    | 106.524                         | 24888892                      | 0.4235                          | 0.0151                          | 136839                         | 0.0149                  | 24888892               | 0.0109                 | 136839               | 0.0091                 |
| 8  | 1067           | 7220691                  | 2216067              | 1356233              | 796488         | 25804         | 11676140                    | 86.092                          | 22972132                      | 0.5758                          | 0.0193                          | 171592                         | 0.0149                  | 22972132               | 0.0109                 | 171592               | 0.0091                 |
| 9  | 362            | 1340692                  | 629867               | 385479               | 101141         | 4159          | 33542200                    | 87.008                          | 35789905                      | 0.1909                          | 0.0101                          | 87012                          | 0.0149                  | 35789905               | 0.0109                 | 87012                | 0.0091                 |
| 10 | 254            | 1190805                  | 518983               | 317618               | 105535         | 3878          | 28245200                    | 88.932                          | 37517927                      | 0.2760                          | 0.0117                          | 115488                         | 0.0149                  | 37517927               | 0.0109                 | 115488               | 0.0091                 |
| 11 | 410            | 1727797                  | 809898               | 495658               | 133011         | 5291          | 46128180                    | 93.066                          | 54997710                       | 0.2101                          | 0.0100                          | 103965                         | 0.0149                  | 54997710               | 0.0109                 | 103965               | 0.0091                 |
| 12 | 363            | 1640091                  | 735695               | 450184               | 126434         | 5026          | 43114190                    | 95.772                          | 37705928                      | 0.2223                          | 0.0105                          | 80655                          | 0.0149                  | 37705928               | 0.0109                 | 80655                | 0.0091                 |
| 13 | 407            | 1730465                  | 835377               | 511125               | 121816         | 5115          | 54154570                    | 105927                          | 41043765                      | 0.1910                          | 0.0097                          | 76802                          | 0.0149                  | 41043765               | 0.0109                 | 76802                | 0.0091                 |
| 14 | 483            | 2022240                  | 871742               | 533506               | 167241         | 6637          | 51756150                    | 97014                           | 48124988                      | 0.2374                          | 0.0115                          | 83855                          | 0.0149                  | 48124988               | 0.0109                 | 83855                | 0.0091                 |
| 15 | 490            | 2572749                  | 1057194              | 647003               | 236186         | 8647          | 69204340                    | 106963                          | 67905988                       | 0.3024                          | 0.0125                          | 99696                          | 0.0149                  | 67905988               | 0.0109                 | 99696                | 0.0091                 |
| 16 | 106            | 463037                  | 222578               | 136218              | 43942          | 1574         | 14668310                    | 107678                          | 13803884                       | 0.2580                          | 0.0105                          | 97004                          | 0.0149                  | 13803884               | 0.0109                 | 97004                | 0.0091                 |

The region name can be found in Figure S2 of Supporting Information, and the rooftop area (fifth column (D)) accounted for 61.2% of the building area (fourth column (C)). [78].
First, the electricity generation per rooftop area was 82,490 kWh/m² (fourth column (B) of Table IV), which ranked 16th among the 16 administrative divisions (fifth column (C) of Table IV). The results showed the energy supply capacity in Seoul inferior to those in the other regions: (i) as shown in Table S4 (Supporting Information), the monthly average daily solar radiation in Seoul is very low, ranking 16th (generally, the monthly average daily solar radiation and the electricity generation tend to be proportional to each other); (ii) as shown in Table S5 (Supporting Information), the monthly average temperature in Seoul is very low, ranking 15th (generally, the monthly average temperature and the electricity generation tend to be inversely proportional to each other); and (iii) as shown in Table S6 (Supporting Information), the latitude of Seoul ranked second, one of the most northward regions, and its meridian altitude at noon of the winter solstice was also very low, ranking 15th (generally, the meridian altitude at noon of the winter solstice and the installation area per unit tend to be inversely proportional to each other). The electricity generation per rooftop area was thus the result of the combination of these characteristics.

Second, the electricity consumption per rooftop area was 213,376 kWh/m² (sixth column (D) of Table IV), which ranked first among the 16 administrative divisions (seventh column (E) of Table IV). From the perspective of energy demand, this result is considered poorer than those in the other regions. This is believed to have been due to the higher population density in elementary schools in Seoul, that is, to the higher number of persons per rooftop or number of classes per rooftop area. The causal relationship between the regional energy supply and demand by elementary school facility will be analyzed in Step 6. Based on this, the regional energy supply and demand strategy will be presented in Step 7.

Third, the energy substitution effect was analyzed by calculating the ratio of the electricity consumption per rooftop area (213,376 kWh/m²; sixth column (D) of Table IV) to the electricity generation per rooftop area (82,490 kWh/m²; fourth column (B) of Table IV). It was calculated as 41.97% (eighth column (F) of Table IV), which ranked 16th (ninth column (G) of Table IV) due to the combination of the aforementioned analysis results with the energy supply and demand in Seoul.

In this process, the energy substitution effect of the 5418 elementary school facilities in the 16 administrative divisions in South Korea was analyzed. The ratio (α) of the available rooftop area to the building area in the education facilities averaged 61.2% and ranged from 37.3% to 92.5% (Table S7 of Supporting Information). If the minimum ratio of 37.3% were to be used, the energy substitution rate in all 16 administrative divisions in South Korea would be below 100 (eighth column (F) of Table S10 of Supporting Information). On the other hand, if the maximum ratio of 92.5% were to be applied, the energy substitution rate in all the regions, except for the metropolitan areas such as Seoul, Incheon, and Gyeonggi, would be over 100 (eighth column (F) of Table S11 of Supporting Information).

3.5. Step 5: Geographical analysis of the regional energy supply and demand

By using GIS, the current regional energy supply and demand was visually presented by the elementary school facilities.
facility through the application of the rooftop PV system from the geographical perspective [86]. A visual map makes intuitive decision for location, which is a key factor for the success of the introduction of the rooftop PV system.

In this study, the software program called ArcMap 10.1 of ArcGIS 10.1 was used. In particular, kriging, a function included in the extension of ArcMap 10.1, which is a type of geographic information system interpolation (GISI), was applied. The kriging is suitable for determining the overall tendency of the region from the macroscopic view. The framework proposed in this study involves mapping of the energy substitution effect in all the 5418 elementary schools in the 16 administrative divisions in South Korea. Thus, kriging was determined to be more suitable for the study.

The kriging is referred to as a geostatistical interpolation technique, which is based on the autocorrelation (i.e., statistical relationships among the measured points (S_i) in Equation (3)). In the kriging method, the weights (\lambda_i in Equation (3)) are calculated based not only on the distance between the measured points (S_i in Equation (3)) and the unmeasured point (S_0 in Equation 3) but also on the overall spatial arrangement among the measured points (S_i in Equation (3)). That is, the kriging is based on minimizing the statistical expectation of the following Equation (3) [86].

$$
\varepsilon = \left( \hat{Z}(s_0) - \sum_{i=1}^{N} \lambda_i Z(s_i) \right)^2 
$$

where \varepsilon is the random error with spatial dependence; \hat{Z}(s_0) is the estimated value at the unmeasured point (S_0); Z(s_i) is the observed value at the measured points (S_i); N is the number of the measured points (S_i) surrounding unmeasured point (S_0); and \lambda_i are the weights assigned to each observed point (S_i).

Figure S2 (Supporting Information) shows the geographical location of the administrative divisions in South Korea, which consist of seven metropolitan cities (Nos. 1–7 in Figure S2) and nine provinces (Nos. 8–16 in Figure S2).

As shown in Step 4, the energy substitution effect of the 5418 elementary school facilities in the 16 administrative divisions in South Korea was analyzed. The result of mapping of the energy substitution effect in Figure 3 can help to immediately determine the energy substitution effect in South Korea. The energy substitution effect by region has a broad spectrum from roughly 30–250%. First, the energy substitution rate of seven metropolitan cities (Nos. 1–7 in Figure 3) and their surrounding areas is below 100% and is marked in green. Particularly, Seoul Metropolitan City (No. 1 in Figure 3), which is the capital of South Korea, and the satellite city, Gyeonggi province (No. 8 in Figure 3) are marked in dark green. On the other hand, the energy substitution rate of the other eight provinces (Nos. 9–16 in Figure 3), marked either in red or in yellow, is over 100%.

Such results can be interpreted with the results of the energy demand analysis shown in Step 3. Figure 4 shows the results of mapping of the energy consumption per
rooftop area, which has a broad spectrum from roughly 50 to 260 kWh/m², and is very different from the result shown in Figure 3. In other words, for the eight administrative divisions (Nos. 1–8 in Figure 3), which are marked in green from the perspective of energy substitution rate, the energy consumption per rooftop area is marked in red or yellow in Figure 4 from the perspective of energy demand. Because of the small difference in the energy generation per unit area in South Korea, the regional energy substitution effect is largely affected by the energy consumption per rooftop area, which is confirmed by Figures 3 and 4.

Step 3 analyzes the number of persons per rooftop area and the number of classes per rooftop area as two factors influencing the energy consumption per rooftop area. The results are shown in Figures S3 and S4 (Supporting Information), respectively. These results show a pattern similar to that of Figure 4. Accordingly, it was determined intuitively that the number of persons per rooftop area and the number of classes per rooftop area directly affect the energy consumption per rooftop area. Step 6 presents the results of the detailed analysis on the correlation between these factors.

Figure S5 (Supporting Information) shows the result of mapping of the regional population per unit area. The detailed values are shown in Table S12 (Supporting Information). The population per unit area in the seven metropolitan cities (Nos. 1–7 in Figure S5 of Supporting Information) and the satellite city, Gyeonggi province (No. 8 in Figure S5 of Supporting Information), is marked either in red or in yellow. In other words, it was confirmed that the population density of these eight administrative divisions is very high. From the aforementioned results, the reason for the red or yellow mark in the energy consumption per rooftop area in the eight administrative divisions can be intuitively determined (Nos. 1–8 in Figure 4). The reason for the red or yellow mark in the number of persons per rooftop area and the number of classes per rooftop area in the eight administrative divisions can also be intuitively determined (Nos. 1–8 in Figures S3 and S4 of Supporting Information).

The preceding identical process was applied to Seoul Metropolitan City (No. 1 in Figure S2 of Supporting Information). Figure S6 (Supporting Information) shows the geographical location of the 25 administrative divisions in Seoul. The energy substitution rate through the application of the rooftop PV system to elementary school facilities, in the region where the city’s administrative duties and office buildings are concentrated (Nos. 1–3 in Figure 5), was shown to be higher than those of the other regions. Because these regions have low residential population densities, the population densities of their elementary school facilities are also low. Accordingly, the number of persons and classes per rooftop area are low, which ultimately results in the low energy consumption per rooftop area (Figures S7–S9 of Supporting Information).

3.6. Step 6: Statistical correlation analysis of regional energy supply and demand

A statistical correlation analysis was conducted to determine the causal relationship between the regional energy supply and demand by elementary school facility [87]. In addition to the result of the intuitive analysis of the visual
mapping result in Step 5, a statistical correlation analysis would show the objectivity of the analysis results.

First, Figure S10 (Supporting Information) shows the correlation between the energy substitution rate and the energy consumption per rooftop area. A very high negative correlation was shown with the correlation coefficient at -0.946, which served as the objective basis of the intuitive analysis results in Figures 3 and 4. Second, Figure S11 (Supporting Information) shows the correlation between the energy consumption per rooftop area and the number of persons per rooftop area. A very high positive correlation was shown with the correlation coefficient at 0.929, which served as the objective basis of the intuitive analysis results in Figures 4 and S3. Third, Figure S12 (Supporting Information) shows the correlation between the energy consumption per rooftop area and the number of classes per rooftop area. A very high positive correlation was shown with the correlation coefficient at 0.936, which served as the objective basis of the intuitive analysis results in Figures 4 and S4 (Supporting Information). Compared to 0.929 in Figure S11 (Supporting Information), 0.936 in Figure S12 (Supporting Information) was shown to be more efficient. Since elementary school facilities are operated by class, the explanatory power of the number of classes per rooftop area is higher than that of the number of persons per rooftop area.

3.7. Step 7: Establishment of the regional energy supply and demand strategy

Based on the results of the regional energy supply and demand analysis by elementary school facility, a regional energy supply and demand strategy is proposed largely from the following two perspectives. Through these strategies, energy supply and demand would be successfully promoted (Table S13 of Supporting Information) [88,89].

First, the following strategies would be established from the perspective of energy supply. For regions with an over 100% energy substitution rate (eighth column (F) of Table IV), the introduction of the rooftop PV system can be proactively recommended. By providing government subsidies as incentives, the central government can promote the proactive participation of local governments. In calculating the size of the government subsidies, the following two factors can be considered: (i) the initial investment cost for the introduction of the rooftop PV system, and (ii) the benefit from the energy conservation through the introduction of the rooftop PV system. Next, for regions with a less than 100% energy substitution rate (eighth column (F) of Table IV), other types of NRE systems such as geothermal energy systems or fuel cells can be recommended. As mentioned previously, the two factors were considered in calculating the size of the government subsidies for regions with an over 100% energy substitution rate. For regions with a less than 100% energy substitution rate, the initial investment cost for the introduction of the other types of NRE systems and the consequent benefit from the energy conservation should be considered.

Next, the following strategies can be established from the perspective of energy demand. As shown in Step 6, the energy demand in a region with a low energy substitution rate is relatively higher than that in a region with a high energy substitution rate. Also, such a region has a higher number of persons or classes per rooftop area. Therefore, for a region with a less than 100% energy substitution rate, policies for reducing the number of persons or classes per rooftop area should be established. Among these policies, the most realistic one would be to increase the number of elementary school facilities in the target region. However, if it is impossible due to various reasons along with the introduction of the rooftop PV system, the introduction of energy-saving measures can
be proactively recommended to reduce energy consumption. For example, according to Hong et al. [90], the ratio of electricity consumption by lighting is high in educational facility, so the introduction of high-efficiency lighting such as LED (light-emitting diode) could be recommended. Along with the aforementioned two factors that were considered in the calculation of the size of government subsidies, the initial investment cost for the introduction of energy-saving measures and the consequent benefits from energy conservation should be considered.

4. CONCLUSIONS

This research was conducted to develop a framework for the analysis of the potential of the rooftop PV system to achieve the nZESBs from the perspective of energy supply. To verify the feasibility of the proposed framework, elementary school facilities were selected for a case study. This research (i) collected information on the elementary school facilities, the rooftop PV system, and the meteorological and geographic characteristics by region; (ii) conducted an energy supply analysis by applying the rooftop PV system; (iii) conducted an energy demand analysis; (iv) analyzed the energy substitution effect; (v) presented the current status of the energy supply and demand in each region using GIS; (vi) analyzed the causal relationship between the energy supply and demand by region; and finally, (vii) proposed an energy supply and demand strategy by region.

The regional energy substitution effect was analyzed through the application of the rooftop PV system in a total of 5418 elementary schools in the 16 administrative divisions in South Korea. Also, mapping of the potential of the nZESBs was proposed using the kriging, a function included in the extension of ArcMap 10.1, which is a type of the GIS. It showed a broad spectrum of roughly 30–250%.

First, the potential of the nZESBs in the seven metropolitan cities (Nos. 1–7 in Figure 3) and the satellite city (No. 8 in Figure 3) was less than 100% and was marked in green, whereas that of the remaining eight provinces (Nos. 9–16 in Figure 3) was more than 100% and was marked in red or in yellow.

The causal relationship between regional energy demand and the results of the analysis of the potential of the nZESBs was also assessed. As shown in Figures 3 and 4, the result significantly differed from each other. Because of the small difference in the energy generation per unit area in South Korea, the potential of the nZESBs was largely affected by the energy consumption per rooftop area. By combining these results, a regional energy supply and demand strategy was proposed.

This research can help elementary school facility managers or policymakers conduct energy supply and demand analysis as well as propose an energy supply and demand strategy. Especially, a visual map of the regional energy supply and demand makes intuitive decisions about location. It can be used as part of an educational facility improvement program. The proposed framework can also be applied to any other country or sector in a global environment. From the macroscopic view, the results of this study can be used in a preliminary feasibility study for the introduction of NREs, particularly for the introduction of the rooftop PV system, in establishing a mid-term to long-term roadmap for achieving South Korea’s national carbon emissions reduction target. From the microscopic view, the results of this study can be used in a preliminary feasibility study for the implementation of the rooftop PV system as a means of reducing the carbon emissions of individual facilities.

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