NPV-BASED 3D ARRAY DESIGN SYSTEM OF ROOF-TOP PHOTOVOLTAICS

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ABSTRACT: On BIPV systems, especially roof-top PV systems, the power generation is easier to be reduced due to the shades of facilities nearby, or roof itself. To secure profitability of roof-top PV systems, the optimal design of solar arrays through the precise shading analysis is an important item of design considerations. In this paper, an optimization system for array design of roof-top PVs is to be developed using three-dimensional Geospatial Information System(GIS). The profitability of income and expense is considered through the shading analysis of entire roofs. By applying the system to project for validation, the adequacy and the improvement of NPV of the system were verified compared to expert's design. The system has significance by reason that PV modules are placed through rules established with expert knowledge and geometric rules were applied to reflect the constructability and maintainability.

Keywords: Roof-top Photovoltaic; Array Design; Net Present Value; 3D GIS

1. INTRODUCTION

The use of new renewable energy, such as photovoltaic power, as an alternative energy source for fossil fuel tends to be constantly expanding. In particular, the photovoltaic market has played a key role in the renewable energy green industry, recording an average annual growth rate of 80% in 2010 alone. To preserve the unit cost of the power generation of the photovoltaic system, which is four times higher compared to the existing thermal and nuclear power generation facilities, governments in each country have been implementing the RPS (Renewable Energy Portfolio Standard), the renewable energy obligation quota system, which is designed for subjects of carbon dioxide emissions and electricity demands to bear the investment costs of renewable energy. The RPS system helps to induce the activation of a building-integrated photovoltaic equipment-driven market by applying relatively higher weights to photovoltaic equipment used in structures, compared to ground photovoltaic installations. Among current BIPV(Building Integrated Photovoltaic System) facilities utilized in structures, the installation of roof-top PV systems in the roof surface of buildings has been actively promoted because of technical issues, such as generation efficiency, helping adjacent facilities and raising generation quantity according to the solar incidence angle.

The installation of roof-top PV systems in the factory's roof or building rooftop is characterized as smaller in scale, compared to ground-type installations, where there is difficulty in the optimization of PV modules and array design, which is attributed to the fact that shading leads to interference in surrounding structures or in its own facilities, such as ventilation monitors or cooling towers, as well as the azimuth and slope of PV installations, due to the location appearing differently even when they are installed in a single structure. For an accurate prediction of generation quality by installation point of PV systems and in the design of the photovoltaic array, these complex elements must be considered in the system design. However, the design of the photovoltaic array is largely performed according to the designers' experiences or intuition in the installation process of roof-top PV systems. In a manual operation, the photovoltaic array is configured by estimating the shadow area in adjacent buildings or in its own facilities based on the winter solstice, when the solar incidence angle is at its lowest. Then again, intuitive methods in designing the photovoltaic array after extracting the shadow area of the building roof, according to the annual trajectory of the sun by utilizing the graphic framework, have mainly been applied to the current photovoltaic design.

In this study, PV3GIS(Photovoltaic based on 3-dimensional Geospatial Information System) that helps address the problems in existing design methods in the module placement of roof-top PV systems in structures is developed. System construction is implemented by conducting precise shading analysis of entire roofs. Finally, an NPV-based, initial photovoltaic array placement method that considers the profitability of the initial input costs and operating costs, and calculates generation income through shading analysis is deduced.

2. RELATED WORK

In relation to the optimization of the array design for PV systems, studies on a variety of subjects, such as shading analysis, economic analysis, and suggestions on design alternatives, have been carried out. In particular, new shading analysis techniques were developed by utilizing previous research to predict the generation loss of the photovoltaic array according to shade [1][4][6] or fish-eye pictures [3]. Studies on the economic analysis of PV systems include a comparative analysis of economic efficiency between PV systems in commercial buildings and ground-type PV systems [2] and the research on estimating the levelized cost of energy (LCOE) through calculation of generation quantity and shading analysis of the inclination of the photovoltaic modules that target PV systems installed in the building roof [5]. Despite the progress of various studies, collectively conducting shading analysis through establishment of expert systems, analyzing generation quantity and economic efficiency, and suggesting alternatives for a substantial design of a photovoltaic array have not been widely practiced.

Among those utilizing GIS, the Sun-Area project of Germany is developing web-based systems that can calculate the scale of investment costs, carbon dioxide reduction, expected generation quantity, and fitness in the plan to install photovoltaic power generation panels in the roofs of houses nationwide to utilize solar energy resources effectively. The Solar Boston program of the US was formulated to construct and utilize a web-based solar map that can analyze photovoltaic energy utilization potential through virtual simulation of buildings and privately-owned houses and determine the amount of carbon dioxide reduction. These studies conducted in Germany and in the US succeeded in coming up with a rough calculation of photovoltaic energy as urban-based projects, but the knowledge and information required for the placement of PV systems, such as the detailed form of the roof, effects on fixtures, and relevant regulations and standards, is still lacking, and was excluded from the research contents.

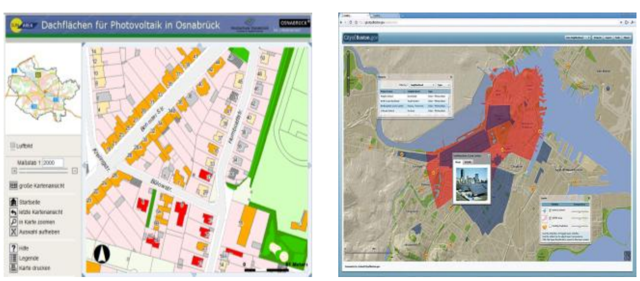

Figure 1. Sun-Area Project and Solar Boston Project

3. CONVENTIONAL DESIGN METHOD

3.1 Key design factors

In selecting the major items that will be reflected in the array design of roof-top PV systems, a survey among experts was carried out. An AHP analysis was conducted, utilizing Expert Choice, a commercial program, targeting pairwise comparison survey results of 12 items for consideration and 4 design areas under government guidelines. As shown in the figure 1, securing proper solar radiation hours through shading analysis was analyzed as the most important design consideration item with 0.284, showing a large gap of more than 50% compared to other items, which reflects the characteristics of roof-top PV systems and shows the analysis on the shadow effects by architectural forms and its own facilities as very important factors in the array design of roof-top PV systems. The second-ranked item in importance is the inverter selection that considers performance and specifications, leading to the interpretation that the selection of inverter performance and specifications, regardless of installation locations and proper placement of serial and parallel design of modules, is also an important consideration item. The third important consideration item is the placement that considers architectural design and field conditions, indicating that array design must conform to the architectural design and conditions in the installation of PV systems in structures.

Design Field	Considerations	Relatively Important
selecting a module and shade analysis/array design	selecting a module considering size/specification	0.069
	array design considering electricity generation capacity	0.050
	building design and array design considering site condition	0.097
	reasonable solar radiation time by shade analysis	0.284
structure design and waterproofing system on stanchion/attachment material	consider for various loads	0.053
	consider for waterproofing	0.043
	rust preventative method	0.025
array electric wiring and junction box	strong connection and sheath protection	0.046
	reasonable install for junction box, ground connection/ a lightning arrester	0.052
	electric wires length modify considering a drop of electric pressure	0.078
selecting and array design an inverter	selecting an inverter considering size/specification	0.147
	array design considering rainwater	0.056

Figure 2. Relative importance of design consideration

In addition to technical considerations in the design of the photovoltaic array, the convenience in the maintenance or cleaning, as well as aesthetic issues regarding the harmony with structures and connection with the surrounding environment, must be likewise considered. It is known that dust or foreign substances in the surface can cause more than 4% degradation in efficiency. It was researched that in the case of the installation of modules with more than 20 degrees of inclination, the dust was removed by rainfall, but the convenience in maintenance must also be considered in other cases. In terms of aesthetic aspects, it is necessary to consider harmony with the urban landscape, arrangement, colors, distance from surrounding buildings, and glare.

3.2 Analysis of the existing design methods

The problems in the design practices in existing methods were analyzed by focusing on 4 items with relatively higher importance in the array design of roof-top PV systems. To secure the proper solar radiation hours through shading analysis, existing methods established non-shaded areas as the zones in which the same isolation is received through the shading analysis of the specific data and time, and placed modules without considering the cost of inputs and generation quantity according to the isolation of the entire roofs. In terms of the inverter selection in which performance and specifications are considered, the serial and parallel configuration and the placement of modules and array were done according to the designers' experiences and judgment. Although the separation distance between roof facilities, separation distance between modules and the array, and separation distance for security and stability are important factors in terms of placement that considers architectural design and field conditions, existing methods were mostly dependent on designers' experiences and judgment. Even in terms of cable length adjustment, which considers the drop in voltage, the degree of the dispersion of modules and the array was judged according to designers' experiences, and placement was adjusted.

To solve the problems of the existing design methods, 5 improvement directions were established. The calculation of isolation in the entire area for 365 days by utilizing the three-dimensional geospatial information system was suggested in the shading analysis. The method to calculate the generation quantity of the entire area individually through the shading analysis results was proposed in the analysis on generation quantity. In terms of profitability analysis, the implementation of the net present value through the calculation of grid-specific income and expenses was suggested.

4. DEVELOPMENT OF PV3GIS

3D drawing is converted into a DSM (Digital Surface Model) file that utilizes the functions of ArcGIS^{TM}. Based on DSM files, the x and y coordinate values and altitude values, an isolation analysis is implemented by using the solar radiation tool of ArcMAP^{TM}. After processing the isolation database and coordinate values in the grid center point calculated in ArcMAP^{TM}, the generation output process is performed. To calculate the generation quantity, the meteorological date and physical properties of the photovoltaic modules are needed. For the meteorological data, the average monthly temperature of applicable points and clarity data are required, and NASA's meteorological data is utilized in this system. For the physical properties of the photovoltaic modules, module efficiency, and temperature coefficients, which were secured through the manufacturing companies, are required. To calculate the grid-specific net present value, cost data must be additionally inputted in the income data of the current system. The input costs of the BIPV system are composed of labor costs, maintenance costs and system expenses of photovoltaic modules, inverter and cabling, etc.

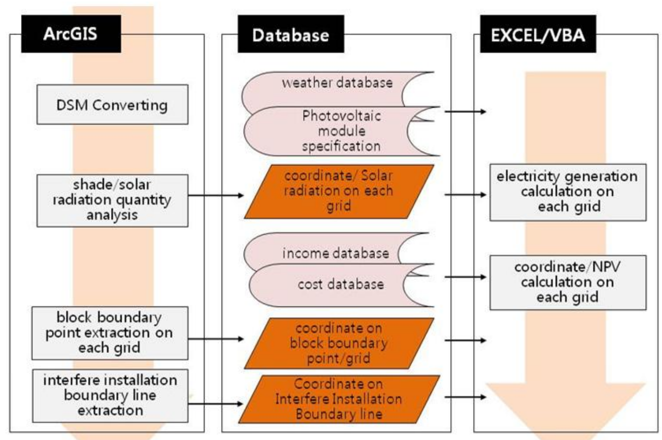

Figure 3. PV3GIS structure

The net present value (NPV), the function of income and expense, is calculated by subtracting the present value of 'expense' from the present value of 'income,' as shown in the following numerical expression (Formula 1).

$$NPV = \sum_{i=0}^{n} \frac{E_i \times P_{sale} - OC_i}{(1+r)^i} - \sum_{i=0}^{n} \frac{CC_i}{(1+r)^i} \qquad \text{(Formula 1)}$$

Here, E_i represents the generation quantity per annual unit area, P_{sale} sales price of electric power, OC_i operating cost per annual unit area, CC_i initial input costs per unit area, r discount rate, and n operating year.

5. VALIDATION

The case for the validation of the PV3GIS system proposed in this study is the roof-top PV system of the factory building located at 127 degrees, 15 minutes, and 4 seconds in the east longitude, and 36 degrees, 54 minutes, and 56 seconds in the north latitude. Since its establishment in October 2010, the factory has been operating after launching its power generation function in November 2010. The size of the building is 73 m in width and 97 m in length, based on the plane projection. The roof plane projection area, in which the placement of PV systems is made possible, is 5,892 ㎡, and it is composed of 4-sided roof blocks with an inclination of 8.4 degrees and an area of 1,213 ㎡ as well as 1-sided roof block with an inclination of 2 degrees and an area of 1,040 ㎡.

Based on the three databases of the interference facilities and installation, except the section and block grid constructed in PV3GIS, photovoltaic modules were placed through the application of 4 regulations, including block boundary separation, separation distance between photovoltaic modules, position exclusion of interference facilities, and position exclusion of installation exception sections. Through PV3GIS, it was analyzed that the overlapping area of the two placement methods is 2,429 ㎡, which constitutes 86.6% of the entire module slope area (2,805 ㎡) of PV3GIS.

Figure 4. CASE and array design using PV3GIS

This result is attributed to the difference in separation distance values reflected in the separation regulations of PV3GIS. The difference in the generation quantity between the two placement methods was very small (about 0.1%).

Table 1. Comparison of PV3GIS with case

Block	PV3GIS			CASE			Overlap rate
	Number of Modules	Capacity (kWp)	Gross generation (kWh)	Number of Modules	Capacity (kWp)	Gross generation (kWh)	
A04	228	31.00	40,64	228	31.00	40,654	88.8%
A06	240	32.64	40,41	244	31.18	41,207	83.5%
A07	240	32.64	42,29	240	32.64	42,300	89.5%
A08	240	32.64	40,84	244	33.18	41,679	83.5%
A05	360	48.96	63,80	352	47.87	62,382	87.5%
Total	1,308	177.88	227,99	1,308	177.88	228,222	86.6%

6. CONCLUSIONS

In this study, the importance of major design items was taken into consideration in the design of roof-top PV systems, whose applications have recently been expanding. After identifying the problems through an analysis on existing design practices, a system for the optimization of the rule-based photovoltaic array design was constructed by utilizing three-dimensional GIS.

This study is significant in terms of the utilization of GIS solutions and three-dimensional drawings through BIM, showing a higher level of its use in recent years, in the application of design methodology differentiated from existing studies, and in the suggestion of decision-making alternatives that meet the government institutions' standards and policies.

The PV3GIS proposed in this study has limitations in the professional knowledge of block boundary separation distance, interference facilities, and location, except some sections, and were not considered, while placement forms are irregular and sporadic since they were deduced based on NPV. In this regard, it is required to develop a system that can relocate the placement methods by NPV in consideration of constructability and maintainability.

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