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Techno-Economic Analysis on Rooftop Solar Energy Potential in Future Seoul

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ABSTRACT

A thorough analysis of the solar energy potential and the utilization cost is necessary to form a public consensus on the active adoption of solar energy in Seoul. This study strives to answer two questions: How much solar energy can all the building rooftops in Seoul produce, and how does the feasibility of rooftop solar energy change, depending on the future development in economic and technological factors until 2050. The research simulates rooftop solar energy production in Mapo District of Seoul and combines it with future scenarios analysis, considering the technological advance in solar PV production systems and the change in economic factors such as wholesale electricity tariff and systems management cost. The study adopts the Ladybug tool, an energy modeling tool connected to a 3D CAD interface of the Rhinoceros program, to simulate hourly rooftop solar energy production in each season based on a digital map and weather data of Seoul. The simulation shows that 72% of the Mapo District's total building electricity consumption in 2020 could have been covered by rooftop solar energy if solar PV panels covered every building rooftop. The three scenarios of benefit-cost analysis project that rooftop solar energy will start to play a crucial role in carbon mitigation between 2026 and 2044. However, the scenarios indicate that the explosive growth of PV panel installation would mean both the exponential increase of benefits and the escalation of costs, resulting in a slower expansion of the technology and higher costs for users. The research result also implies that increasing the supply of rooftop solar energy is not the sole essence of bringing solar city development to realization. As the transition to green energy involves uncertainty, a precise prediction of the potential amount of the source and consideration of the technological and economic usability will help achieve a feasible energy supply plan aiming for a slight burden on consumers in urban areas.

Keywords: Carbon neutral strategy, techno-economic analysis, renewable energy supply system, rooftop solar energy

1. INTRODUCTION

During the 26th UN Climate Conference of the Parties in 2021, South Korea newly announced the suspension of coal thermal power generation and investment in fossil fuel power plants on a national level [1]. However, current energy policies announced by the South Korean government do not appear to support the country's international movement. Especially the renewable energy supply plans failed to contain the precise calculation of potential productivity. For an energy source, estimating the future yield is important because it is highly related to the feasibility of the source. According to the Education Committee of the National Assembly in 2020, the photovoltaic panels installed on the rooftops of 3149 public schools could not retrieve the investment cost within the average 25-year lifespan of the panels [2]. Considering Korea's public nature of energy, the unfeasibility directly links to a national loss.

Despite the numerous studies on rooftop solar energy potential, the field requires more delicate bottom-up calculation and more inclusive projection at an urban scale. The top-down approach, which uses the amount of solar radiation and rooftop area for calculation, has been a popular research method in this field. However, this method is inaccurate in calculating the rooftop area. The building area is often considered equal to the rooftop area, or the rooftop area coefficient drawn out from the literature review is multiplied by the building area [3, 4]. Although there certainly exists bottom-up research at the urban scale [5, 6], cases of

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projection studies combined with economic and technological feasibility measurement are still rare. Especially in Korea, the existing bottom-up research is insufficient in fulfilling the goal of estimating solar energy production at the urban scale. [7] and [8] only included a particular type of building or area, whereas [9] only measured the amount of solar radiation rather than the amount of solar energy produced by PV panels. Moreover, there needs more techno-economic projection research that takes spatial and temporal dimensions into account, as in the case of [10].

This study will answer the following two questions. The first question is, 'How much solar energy can rooftops produce in Seoul?'. As both the Paris Agreement and the Glasgow Climate Pact aim to constrain the earth's temperature increase by 1.5 ℃ until 2050 compared to the period before industrialization [1], the temporal range in the analysis is set up to 2050 as well. The second question is, ‘How does the feasibility of rooftop solar energy change depending on the future development in economic and technological factors until 2050?'. From the user perspective, this study assumes that the cost change in rooftop solar energy production systems caused by technological improvements and changes in economic situations will be the primary determinant in people's decisions to use the technology.

2. STUDY AREA AND DATA COLLECTION

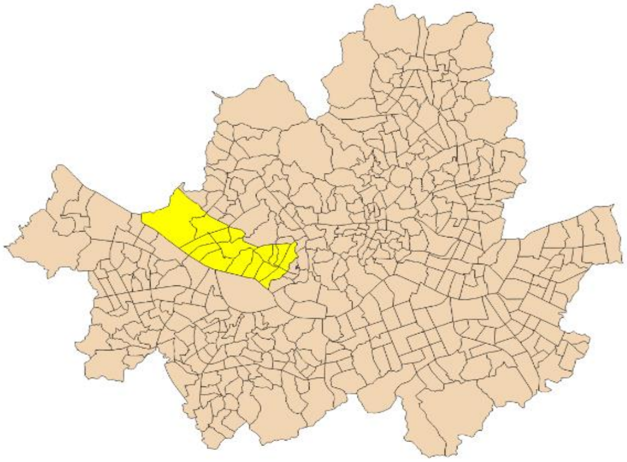


Figure 1. GIS Map of Seoul and Mapo District

As seen in Figure 1, the study area is Mapo District (Gu) in Seoul. Among the 25 districts (Gu) of Seoul, Mapo District shows the best similarity with the entire city in terms of average real estate price [11], land use, and the ratios of total area, population, and GRDP [12], as shown in Table 1. Therefore, this representative district of Seoul was selected as the study area in this research.

Table 1
Seoul and Mapo District.

		Seoul	Mapo District
Land Use (2020)	Residential Area	53.84%	56.05%
	Commercial Area	4.23%	3.94%
	Green Area	38.64%	40.01%
Total Area (2021)		100%	3.94%
Total Population (2022)		100%	3.89%
GRDP (2019)		100%	4.83%
Average real estate price (2022.08.13)		KRW 1,314,240,000	KRW 1,347,350,000

For constructing 3D buildings in the research area, seamless digital maps of 11 areas in Mapo District were downloaded from National Geographic Information Institute. EPW weather file of Seoul in 2020 for solar energy production simulation was obtained from https://www.climate.onebuilding.org.

3. METHODOLOGY

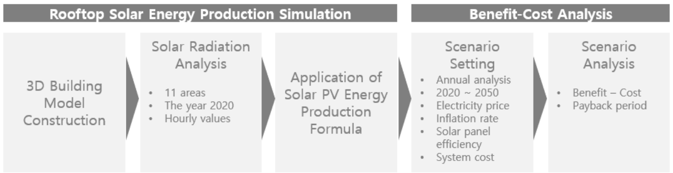


FIGURE 2. Structure of the research

3.1 Simulation of rooftop solar energy production

The study comprises two parts (Figure 2). For the simulation part, the buildings in 11 areas of Mapo District are constructed in 3D models. Next, the hourly amount of solar radiation on the rooftops is measured for every season in the base year 2020. These processes are developed by using the Ladybug tool in the Rhinoceros program. Rhinoceros is a 3D modeling software program utilized by architects, engineers, and designers. Inside the program, there is the Ladybug tool for climate-related energy modeling. Figure 3 is an example of rooftop solar radiation analysis performed with the Ladybug tool.

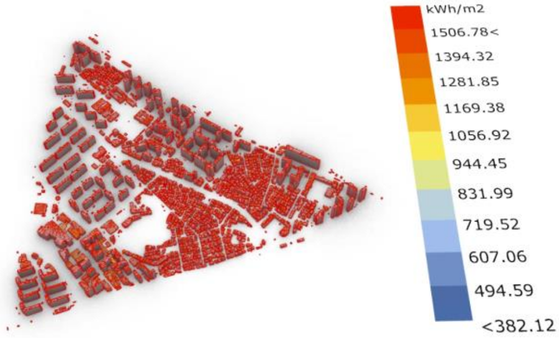


Figure 3. An example of 3D building models

Then, the solar panel production formula below takes the radiation analysis result as the input variable (Pmp0) to calculate the amount of solar energy produced (Pmp). The calculation system is built in Microsoft Excel 2016.

$$P_{mp} = P_{mp0} \times [1+\Gamma \times (T_c - T_0)] \text{ [5]} \qquad (1)$$

$$T_c(°C) = T_a + [T_0 - 20(°C)]/800(W/m^2) \times S(W/m^2) \text{ [13]} \qquad (2)$$

- P_{mp0}: Maximum production under the ideal condition
- Γ: Temperature correction factor
- T_c: PV surface temperature
- T_0: Nominal operating PV cell temperature
- T_a: Ambient temperature
- S: Radiation

The photovoltaic panel model used in this simulation is 'Q.PEAK DUO XL-G9.3' manufactured by Hanwha Q-CELLS. The product guidebook explains that the efficiency is approximately 20%, the correction factor of the model is set at -0.35, and the nominal operating panel cell temperature is set at 43±3°C. The same numbers are applied in the calculation system, and the average temperature of each season in 2020 is assumed to be the ambient temperature.

3.2 Definition of scenarios

As seen in Table 2, different assumptions on both the technological advancements and economic situations for producing rooftop solar energy in the future Mapo District are reflected in three scenarios. Scenario 1 supposes a slow technological improvement and stationary economic situation, while scenario 2 and scenario 3 expect moderate and drastic change each.

Table 2
Scenario definition.

	Scenario 1	Scenario 2	Scenario 3
PV panel efficiency development rate	1%	2%	4%
Inflation rate	1.6%	1.6%	1.6%
PV panel installation/management price decrease rate	0%	0%	-1%
Electricity price increase rate	0%	5% (~2035), 2.6% (~2050)	12% (~2035), 9.8% (~2050)
PV panel area increase rate	0%	19% (~2030) 6% (~2050)	46% (~2030) 23% (~2050)

Solar panel efficiency is expected to grow up to 68% maximum [14]. Assuming the maximum efficiency can be reached by 2050, it is expected that the efficiency will develop by 4% annually over 30 years. So, the 4% value has been set for scenario 3, with the value halving for the other two scenarios.

An average of 1.6% future inflation rate until the year 2030 was estimated by the National Assembly Budget Office in 2021 [15]. The same percentage was adopted for the inflation rate in this projection. Solar panel system price at a utility scale is expected to decrease from \$1.7/W in 2020 to \$1.25/W in 2050 [16]. Therefore, the annual decrease rate is calculated as 1% over the next 30 years only in scenario 3.

Table 3
Electricity tariff projection.

	2020-2025	2026-2030	Decrease rate
Case 1	3%	1.6%	0.52
Case 2	8%	6%	0.82
Multiple	2.4	3.8	-
	2020-2035	2036-2050	Decrease rate
Scenario 2	5%	2.6% (= 5%×0.52)	0.52
Scenario 3	12% (= 5%×2.4)	9.8% (= 2.6%×3.8)	0.82

When only existing demand causes an electricity price increase, the tariff is expected to increase by 3% from 2020 to 2025 and 2% from 2026 to 2030 [17]. However, when the tariff increase is caused by renewable energy production growth, the increase rate grows to 8% and 6%, respectively [17]. These two situations were applied to scenario 2 and scenario 3. During the past ten years, tariffs showed an average 5% increase [18]. So the initial increase rate for scenario 2 is set as 5%. For scenario 3, the initial increase rate was set as 12%, which is the result of 5% multiplied by the multiple 2.4 from Table 3.

Table 4
PV panel area increase rate.

	Scenario 2	Multiple	Scenario 3
500GW~2840GW (2020~2030)	19%	×2.4	46%
2840GW~8519GW (2030~2050)	6%	×3.8	23%

The cumulative installed capacity of solar panels worldwide is expected to grow from 500GW in 2020 to 2840GW in 2030 and reach 8519 GW in 2050 [19]. As seen in Table 4, the annual PV panel area increase rates for scenario 2 are set at 19% and 6% for the respective period. For scenario 3, the two multiples from Table 3 were multiplied by 19% and 6%, respectively.

3.3 Benefit-cost analysis

The benefit of using PV panels is equivalent to the amount of money that can be saved from using traditional fossil fuels. Therefore, it can be expressed as an equation of the amount of electricity generated by PV panels (Pmp) multiplied by the wholesale electricity tariff. But as the 'Pmp' is the amount of solar energy under the assumption of a 100% rooftop utilization rate, the assumptive utilization rate is additionally considered. The initial rooftop area utilization rate is set as 1.3%, which is solar energy production divided by the total building electricity demand in 2020, Seoul [20], and the wholesale electricity tariff of 275.6 (KRW/kWh) in 2020 is adopted [21].

The cost of using PV panels consists of installation and management fees. First, the number of PV panels that fill the total used rooftop area must be estimated. As installation fees and management fees are usually set per 3 kW facility, seven panels (445w/panel) had to be made into one array. Then the number of arrays is multiplied by the installation fee of KRW 8,000,000 [22] and the annual management fee of KRW 160,000 [23]. It should be noted that only the increased areas over the years are reflected in the annual installation fee calculation. Finally, cumulative benefit-cost is examined to capture the payback period.

For further implications, two variations are made for both scenario 2 and scenario 3. Scenario 2.1 and scenario 3.1 assumes there will be no change in the electricity tariff. On the other hand, scenario 2.2 and scenario 3.2 suppose there will be no change in the PV panel areas.

Table 5

Transformed versions of scenarios 2 and 3

	Scenario 2.1	Scenario 2.2	Scenario 3.1	Scenario 3.2
Electricity price increase rate	0%	5% (~2035), 2.6% (~2050)	0%	12% (~2035), 9.8% (~2050)
PV panel area increase rate	19% (~2030) 6% (~2050)	0%	46% (~2030) 23% (~2050)	0%

4. RESULTS

The simulation demonstrates that 1,306,687,752 kWh of electricity from 4,248,230 m^2 of rooftop areas in Mapo District could have already been produced in 2020. This amount of electricity could have covered 72% of the district's annual electricity consumption (1,813,426,000 kWh) [20].

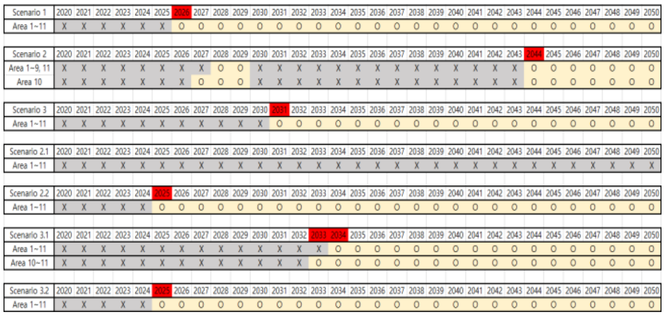
Table 6

Amount of rooftop solar energy production

2020 Energy consumption 1,813,426,000 kWh	Total Solar Energy (kWh)	Self-efficiency rate
2020 (100% Roof)	1,306,687,752	72%
2020 (20% Roof)	14,765,572	0.8%
Scenario 1 2030	16,310,377	1%
Scenario 1 2050	19,901,760	1%
Scenario 2 2030	101,942,085	6%
Scenario 2 2050	871,013,311	48%
Scenario 3 2030	961,305,887	53%
Scenario 3 2050	4,238,107,802	234%

Scenarios 1, 2, and 3 show that rooftop solar energy will become a viable energy source between 2026 and 2044. However, considering that scenario 2 reflects a better environment for rooftop solar production, it is interesting to find out that the break-even point in scenario 2 is predicted to be eighteen years later than that of scenario 1.

The investment cost cannot be retrieved within the given period in scenario 2.1. And the payback periods in 3.1 are extended a couple of years on average compared to scenario 3. On the other hand, the payback periods in scenarios 2.2 and 3.2 are shorter than the original scenarios.



Scenario 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Area 1~11	X	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Scenario 2	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Area 1~9, 11	X	X	X	X	X	X	X	X	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	O	O	O	O	O	O
Area 10	X	X	X	X	X	X	X	O	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	O	O	O	O	O	O

Scenario 3	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Area 1~11	X	X	X	X	X	X	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Scenario 2.1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Area 1~11	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Scenario 2.2	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Area 1~11	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Scenario 3.1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Area 1~11	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Area 10~11	X	X	X	X	X	X	X	X	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Scenario 3.2	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Area 1~11	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Figure 4. Payback periods for each scenario

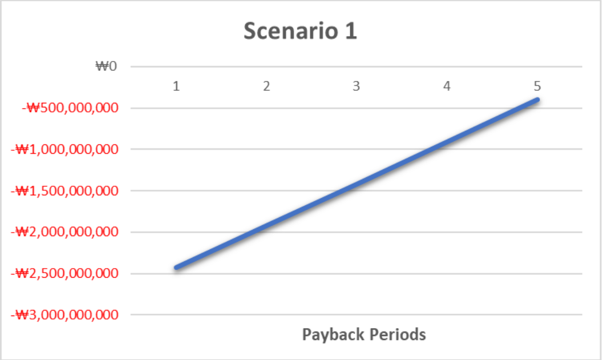


Figure 5. Benefit-cost analysis during the payback periods of Area 1 in scenario 1

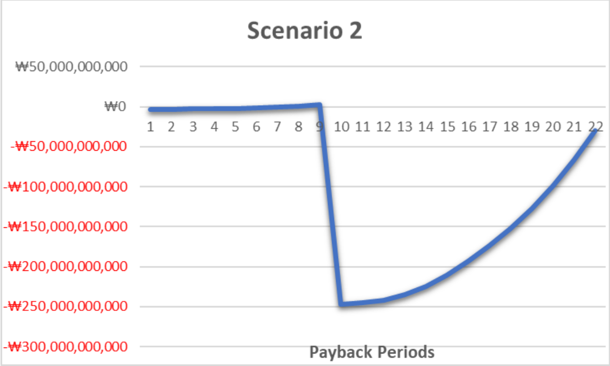


Figure 6. Benefit-cost analysis during the payback periods of Area 1 in scenario 2

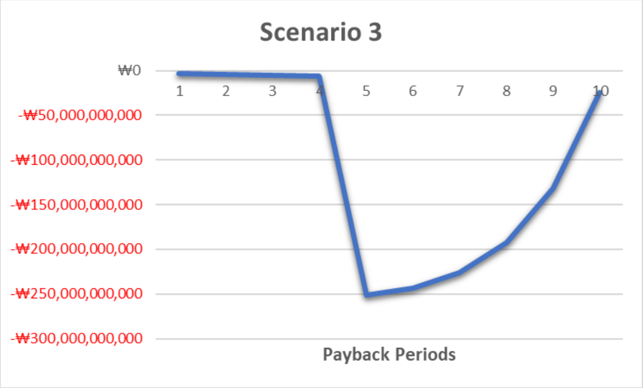


Figure 7. Benefit-cost analysis during the payback periods of Area 1 in scenario 3

5. DISCUSSION

The comparison between Mapo District's total rooftop solar energy production and the total building electricity consumption in 2020 indicates that rooftop solar energy will play a crucial role in reaching a net zero goal in the building energy sector.

As the speed of rise in electricity price and of increase in photovoltaic panel area is fast in scenarios 2 and 3, it was reasonable to expect those scenarios to have suggested an earlier future of rooftop solar energy utilization than scenario 1. However, the result is different from the expectation. As the payback period is longer in scenario 2 than in scenario 1, it would be meaningful to note that the relativity between benefit and cost plays a significant role in determining the feasibility of the energy source. Moreover, the fast adoption of the technology will aggravate the burden on users, as shown in Figure 5. Therefore, the users must have solid financial fundamentals to overcome the financial stress at the initial stage of adoption.

The results of the extended and shortened payback periods shown in the transformed versions of scenarios 2 and 3 indicate that adopting the technology more when there is no increase in benefits will burden the users. Therefore, policy enforcement on solar photovoltaic technology usage should be made when the energy source is expected to become more beneficial in the future.

6. CONCLUSION

The research demonstrated rooftop solar energy supply simulation in Seoul, integrated with techno-economic analysis under three different scenarios from 2020 to 2050. Throughout the 3D building modeling, the study proves that Mapo District (Gu) is rich in solar energy, being able to have produced 72% of the district's total electricity consumption already in 2020 if all the rooftops were covered with solar PV panels. However, it seems more reasonable to view the contribution rate as 0.8%, with only 1.3% of the current building rooftops utilizable.

The study aimed to figure out from which year the adoption of rooftop solar energy will be accepted as feasible. The benefit-cost analysis under the techno-economic scenarios showed that the energy source becomes viable between 2026 and 2044 in most of the areas in Mapo District.

The comparison of the scenario results points out that the incremental financial burden following the explosive installation of solar PV panels may hinder the realization of the initial objective, despite the belief that a more intense application of solar PV panels will bring the earlier future of the solar city. Therefore, a careful inspection of the user's financial status must be preceded before the introduction of the technology.

This study has a few limitations due to the assumptive feature of forecasting the future and the simplification in reflecting real-world situations. For example, setting the future rates of techno-economic factors including inflation, PV panel area, and PV panel efficiency could only rely on subjective allocation by reviewing existing works. Also, this work omitted to take the energy loss during the AD-CD conversion in solar PV production systems into account. Moreover, the simulation is inclusive for the types of buildings because the simulation assumes panels are installed even on stadiums and small rooftops at the entrance door of each apartment building. Lastly, the simulation model may lack some accuracy due to the ignorance of context around the analysis area, and the assumption of flat roofs.

In conclusion, with careful analysis of the technological and economic factors affecting the feasibility of adopting rooftop solar PV panels, it is promising that the abundant potential of rooftop solar energy will significantly contribute to the future of decentralized solar energy production in cities.

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REFERENCE

[1] Moon J, Lee S. 2021 Discussions and Implications regarding COP26. World Economy Today. Korea Institute for International Economic Policy; 2021.

[2] Park M. Growing solar energy market, positive and negative sides. Economic review. https://www.econovill.com/news/articleView.html?idxno=414307

[3] Koh J, Kwon O. A Study on Gyeonggi-Dos Community Energy Potential and Policy Implications. GRI REVIEW. 2019; 21(2):231-58

[4] Lee J, Suh K. Evaluation and Comparison of the Regional Technical Potentials of Renewable Energy for Energy Self sufficient Cities. Journal of Korea Planning Association. 2015; 50(6):189-201

[5] Jakubiec J, Reinhart C. A Method for Predicting City-wide Electricity Gains from Photovoltaic Panels Based on LiDAR and GIS Data Combined with Hourly Daysim Simulations. Solar Energy. 2013; 93: 127-43

[6] Cheng L, Zhang F, Li S, Mao J, Xu H, Ju W, Liu X, Wu J, Min K, Zhang X, Li M. Solar energy potential of urban buildings in 10 cities of China. Energy. 2020; 196.

[7] Kim H, Yu J, Ku Y. An Analysis of PV Potential In Public Buildings of Anyang City. Journal of Korean Society of Urban Environment; 2012

[8] Lee K, Shin M. A Study on the Installation Potential of Photovoltaic System Based on Regional Architectural Data. Journal of the Korean Solar Energy Society. 2019; 39(3):29-45

[9] Kim Y. Analysis of Shadows Effect in Seoul Area for the Estimation of Roof-type PV Power Calculation. Journal of the Korean Solar Energy Society. 2018; 38(1):45-53

[10] Alhammamia H, An H. Techno-economic analysis and policy implications for promoting residential rooftop solar photovoltaics in Abu Dhabi, UAE. Renewable Energy. April 2021; 167:359-368

[11] KB Real Estate. https://kbland.kr/

[12] Seoul Open Data Plaza. https://data.seoul.go.kr/

[13] Amerisolar. https://www.weamerisolar.eu/what-is-nominal-operating-cell-temperature/

[14] Kiss G, Jansen H, Castaldo V, Orsi L. The 2050 City. Procedia Engineering. 2015; 118:326-355.

[15] National Assembly Budget Office. NABO Medium-Term Fiscal Projection 2021~2030; 2021.

[16] NREL. https://atb-archive.nrel.gov/electricity/2018/index.html?t=su

[17] Hyundai Research Institute. Residential electricity tariff raise forecast according to the carbon neutral policy; 2017.

[18] KEPCO. https://home.kepco.co.kr/kepco/EB/A/htmlView/EBAAHP005.do

[19] IRENA. FUTURE OF SOLAR PHOTOVOLTAIC; 2019.

[20] Seoul Energy Information Platform. https://energyinfo.seoul.go.kr/tems/dashboard/engyTransStatus.do

[21] KEPCO. https://cyber.kepco.co.kr/ckepco/front/jsp/CY/E/E/CYEEHP00201.jsp

[22] KDI Economic Information and Education Center. https://eiec.kdi.re.kr/publish/naraView.do?cidx=10932

[23] Lee K, Kim K. Constructing and managing the system for medium-and long-term projection on LCOE for the promotion of renewable energy (1/5). Korea Energy Economics Institute; 2020