**Derivation of Supply Curve of PV ~**

**Impact of Setback regulation ~**

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**Abstract**

This study investigates the impact of setback regulations on the potential for solar photovoltaic (PV) deployment in Gyeonggi Province, South Korea. Using a GIS-based approach, the research analyzes the availability of suitable land, installation capacity, and annual generation potential under both current and relaxed regulatory scenarios. The study also evaluates the economic feasibility of PV deployment by constructing a geospatial supply curve, highlighting the cost-effectiveness of various land-use types. The findings reveal significant variations in PV potential and efficiency across different land-use categories, emphasizing the importance of policy adjustments tailored to regional characteristics. By addressing the interplay between regulatory frameworks, land-use efficiency, and renewable energy goals, this study provides valuable insights for optimizing PV deployment strategies in densely populated and land-constrained areas. These results contribute to the broader discourse on sustainable energy transitions and policy innovation for carbon neutrality.

2.2 Calculation of PV potential 섹션은 아직 챗짚 안돌림.

**Keywords:** Keword1, Keword-2, Keyword-3

1. Introduction

As the 13th largest greenhouse gas (GHG) emitter, South Korea accounted for 1.3% of global GHG emissions [1]. The country has pledged to achieve its nationally determined contribution (NDC) by 2030 and carbon neutrality by 2050 [2,3]. Like many nations, South Korea views the expansion of renewable energy as a key strategy for decarbonization. Globally, renewable energy accounted 27.8% of total electricity generation, whereas in South Korea, the share was significantly lower at 6.1% [4]. Despite this disparity, South Korea decided to lower the 2030 renewable energy target from 30% to 22% [5]. The decision is based on the current government’s willingness to enlarge the role of nuclear power in the middle of energy transition.

In 2021, global renewable energy generation amounted to 7,857TWh, with hydro energy accounting for 4,400 TWh (56%), wind energy for 1,838 TWh (23%), solar energy for 1,033 TWh (13%), and other renewable sources contributing 586 TWh (8%). In 2022, South Korea generated a total of 50.4 TWh from renewable sources, with 30.7 TWh (61%) from solar energy, 11.9 TWh (24%) from bio energy, 3.4 TWh (7%) from wind energy, 3.5 TWh (7%) from hydro energy, and 0.8 TWh (1%) from other source [6]. Comparing South Korea with the global renewable energy mix reveals significant differences in resource dependency. Globally, hydro energy dominates, accounting for 56% of total renewable generation, whereas South Korea relies heavily on solar energy, which constitutes 56.6% of its renewable energy production, far surpassing the global average of 13%. Unlike the global trend where hydro and wind energy prevail, South Korea’s renewable energy strategy hinges on solar energy, emphasizing the importance of scaling up its adoption to secure a sustainable energy transition.

According to South Korea’s carbon neutrality scenario, renewable energy generation in 2050 is projected to reach 889.9 TWh under ‘Scenario A’ and 736.0 TWh under ‘Scenario B’. Assuming the current share of solar energy in renewable generation (61%) remains constant, solar power generation in 2050 would amount to 542 TWh under ‘Scenario A’ and 449 TWh under ‘Scenario B’. Given that South Korea’s the theoretical, technical, and economic PV potential in 2020 was estimated at 137,347 TWh/year, 3,117 TWh/year, and 495 TWh/year, respectively [7], the minimum required amount (449TWh) for carbon neutrality can likely be met if the economic potential (495TWh) is fully utilized. However, only 6% (30.7TWh) of the economic PV potential is currently being utilized.

Several factors contribute to the underutilization of PV potential. The composition of the renewable energy portfolio and energy mix is shaped by a variety of influences, including the natural environment, energy security, economic consideration and politic factors [8]. While energy policies can promote renewable energy expansions by internalizing its positive externalities [9,10], certain regulations may act as barriers. These restrictions, though aimed at preventing the rapid and poorly planned expansion of renewable energy, inadvertently hinder its development.

In many countries, environmental licensing is cited as a major cause of delays in renewable energy projects [11–15]. In South Korea, the issue of setback regulation has sparked significant controversy. These regulations require PV facilities to maintain a minimum distance from designated areas such as residential zones, roads, parks, and cultural heritage sites to be eligible for installation. This has largely been driven by local opposition to PV installations, leading many local governments to enforce setback regulations [16]. Local residents often resist PV facilities due to concerns about environmental degradation and visual impacts [17–20]. Although efforts such as sharing economic benefits from PV projects [21–24], involving residents in the development process [25], and building trust in PV systems [26] have been introduced to improve acceptance, resident opposition remains a significant barrier to the expansion of PV facilities.

In South Korea, setback regulations are particularly detrimental due to two key factors: (i) the country's heavy reliance on solar energy and (ii) its limited land availability. As noted earlier, 61% of South Korea's renewable energy generation is derived from solar power. Furthermore, South Korea ranks 22nd globally in population density, with 530 people per square kilometer among 216 countries [27]. These factors make it challenging to identify suitable sites that meet all the conditions for installing PV facilities. As a result, assessing the impact of setback regulations on PV potential is a critical priority for South Korea.

Previous studies indicate that under nationwide setback regulations, only 23% of potential PV generation (566 TWh out of 2,507 TWh) can be utilized. However, relaxing these regulations to 300 meters and 100 meters could increase the utilization rate to 25% (625 TWh) and 54% (1,365 TWh), respectively [28]. In Incheon province, which experiences the least restrictive setback regulations, 68% of the potential site area is usable. In contrast, regions such as Chungbuk and Chungnam, which face the strictest regulations, can only utilize 22% of their potential site areas [29]. Additionally, in specific counties like Hampyeong (Jeollanam-do), Hamyang (Gyeongsangnam-do), and Gumi (Gyeongsangbuk-do), setback regulations restrict the available PV installation areas to 54%, 53%, and 32%, respectively [30].

This study aims to assess the impact of setback regulations on PV potential in Gyeonggi Province, one of South Korea’s 17 provinces. Gyeonggi Province comprises 31 cities, of which 12 cities have implemented setback regulations. These regulations primarily pertain to minimum distances from residential areas and roads, with setback distances ranging from 100 meters to 500 meters (see Supplementary data for further details). Gyeonggi Province, the focus area of this study, accounts for 10.2% of South Korea’s total area [31] and is home to 27% of the population [32]. It is the region where the introduction of renewable energy is most urgently needed among South Korea’s 17 provinces [33]. First, a regional differential electricity pricing system is under discussion, where a region’s electricity self-sufficiency rate is expected to determine retail electricity prices. From 2019 to 2021, Gyeonggi’s average electricity self-sufficiency rate was 59.34% [34], necessitating an increase in power supply to avoid economic losses from rising electricity prices. Second, 7 headquarters and 17 facilities of global RE100 companies are located in Gyeonggi Province [35,36]. Providing these companies with locally produced renewable energy (e.g., through PPAs) will help them achieve their RE100 goals and mitigate economic losses. Third, the governor of Gyeonggi Province is strongly committed to expanding solar power [37]. Despite the national renewable energy supply target being reduced in the 10th Basic Plan for Electricity Supply and Demand, the governor has set an ambitious goal of installing 9 GW of solar power during his term. In this context, the expansion of solar power in Gyeonggi Province is crucial.

This study focuses on Gyeonggi Province and follows the methodology outlined in Figure 1. First, the study categorizes potential PV installation sites in Gyeonggi into nine land-use types. Using GIS tools, areas suitable for PV installation are identified, excluding currently installed PV sites, mountains with slopes exceeding 15 degrees, and legally protected farmland and mountainous area. The impact of setback regulations is examined by applying various scenario-based approaches. Through spatial analysis, the areas of individual land-use types are calculated, and factors such as area, density, and capacity are used to estimate the annual generation potential of these sites. Additionally, this study incorporates LCOE (Levelized Cost of Electricity) analysis based on the locations and land-use types of the sites to derive the geospatial supply curve. The analysis is used to propose three strategies: quantity-based strategy, price-based strategy, and full deployment strategy. These strategies are then assessed for their impact on generation capacity, greenhouse gas reductions, and costs under setback regulation scenarios.

The key distinctions of this study are as follows: (i) it identifies potential PV sites based on both land-use types and technology types (details provided in the supplementary materials); (ii) the parameters used to convert site area into annual generation potential are derived from observed values in actual PV installation cases, enhancing the realism of the estimated potential; (iii) it evaluates the economic potential of PV generation in a step-by-step manner. This study incorporates technical potential conditions, accounts for protected area regulations, and applies scenario-based setback regulations to provide a comprehensive analysis. Additionally, it integrates economic feasibility into the analysis to derive economic potential. By examining both legal regulations and economic viability, this study offers a multidimensional perspective on factors influencing PV potential. (iv) Unlike previous research, which primarily focuses on deriving the geospatial supply curve of PV generation, this study goes further by developing deployment strategies based on the geospatial supply curve and analyzing the benefits and costs of each strategy to provide policy-relevant insights.

The primary objective of this study is to evaluate the impact of setback regulations on PV potential in Gyeonggi Province. By utilizing GIS-based analysis, the research examines how setback regulations influence PV installation potential across various land-use types and geographical conditions. The study further investigates the implications of setback regulations on solar energy deployment strategies, with a particular focus on generation potential, cost-efficiency, and emissions reduction. Additionally, by deriving a geospatial supply curve, the research assesses the economic feasibility of PV deployment under diverse scenarios, providing insights into optimal strategies for achieving renewable energy targets. This comprehensive approach aims to inform policy discussions by balancing regulatory frameworks with the urgent need for renewable energy expansion, especially in a densely populated and land-constrained region like Gyeonggi Province.

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Fig. 1. Study flow

1. Methodology
   1. GIS-based approaches

Land-use types exhibit distinct socioeconomic and physical characteristics. For example, from a legal perspective, central and local governments establish management and planning regulations for each land-use type. From an economic perspective, cases like AgroPV emphasize balancing agricultural revenue with income from solar power generation, whereas in commercial areas, potential restrictions on business activities (e.g., parking space or rooftop use limitations) must be evaluated. In terms of social aspects, residents in densely populated commercial areas may show low acceptance of PV installations due to aesthetic concerns. Moreover, physical differences among land-use types are notable. For example, mountainous areas might have high capacity factors due to the lack of tall surrounding structures, but issues such as slope stability and soil condition require attention. Additionally, while industrial complexes and residential buildings can leverage existing infrastructure for PV installation, farmland and mountainous regions often require significant land preparation. Given these multidimensional differences, governments implement solar deployment policies tailored to specific land-use types [38–40]. Reflecting these distinctions, this study categorizes potential PV installation sites into nine land-use types to contribute to effective policy formulation.

* Industrial complex: designated under the "Industrial Sites and Development Act" to promote balanced industrial development and national economic growth. (ex. national industrial complex, general industrial complex, urban high-tech industrial complex, agricultural industrial complex)
* Logistics complex: designed for the storage, management, collection, delivery, and adjustment of cargo supply. These facilities often include areas for loading, sorting, packaging, and labeling. (ex. storage facilities, logistics terminals, inland logistics bases)
* Residential complex: designed to accommodate multiple households within a single structure. These complexes allow independent living spaces while sharing walls, corridors, stairs, and other communal facilities. (ex. apartments, row houses, multiplex housing. studio apartments, officetels)
* Public building: constructed by the government, local governments, or affiliated institutions to enhance public convenience and provide essential services. (ex. cultural centers, sports complexes, parks, and other public amenities.
* Mountainous area: Land predominantly covered with forests, including trees and bamboo. These areas exclude farmland, grassland, residential areas, and road sites. Mountainous areas often serve ecological, recreational, or conservation purposes. (ex. Forested mountains and conservation woodlands)
* Farmland: used for cultivating crops, including fields, paddies, orchards, and perennial plant cultivation sites, regardless of their legal classification. Grasslands established under the "Grassland Act" or other exceptions specified by presidential decree are excluded. (ex. paddy fields, dry fields)
* Parking lot: designated for automobile parking as defined by the "Parking Lot Act". Parking lots serve nearby buildings or facilities and may also be available for public use. (ex. On-street parking lots, off-street parking lots, attached parking lots, public parking lots, private parking lots)
* Roadside land: unused spaces between roads and road facilities, often managed as green spaces by the Korea Expressway Corporation. These areas may also serve as potential locations for renewable energy projects. (ex. interchanges, junctions, toll stations)
* Inland water treatment area: designed to store or manage water in rivers, river zones, or coastal areas to secure agricultural and rural water supply. (ex. reservoirs, lakes, dams)
  + 1. Geographical constraint

Certain legal regulations make it impossible to install PV systems in specific areas of farmland and mountainous areas. Among mountainous areas, PV installations are prohibited in preserved mountainous districts. These preserved mountainous districts are further categorized into mountainous districts for forestry use and mountainous districts for public interest. Mountainous districts for forestry use are designated by the Korea Forest Service to enhance forestry production functions, such as forest resource creation and forestry management infrastructure development. Mountainous districts for public interest are designated to serve both forestry production and public purposes, such as disaster prevention, water resource protection, biodiversity conservation, landscape preservation, and public health and recreation enhancement. Additionally, even if an area is not designated as a preserved mountainous district, regions with an average slope exceeding 15 degrees are prohibited from PV system installation.

Farmland classified as agricultural promotion areas is not permitted to host PV systems, and agricultural protection areas larger than 1 hectare are also prohibited from PV installations. This study applied these regulations on PV installation when assessing site feasibility. The setback regulations, however, are discussed separately in 2.4 Scenario section.

* 1. Calculation of PV potential

The annual (8,760 hours) theoretical potential generation ( in kWh) of PV in a given site () with area ( in m2) can be calculated based on the global horizontal irradiation ( in kW/m2) using the following equation (1).

(1)

However, the theoretical potential has limitations in providing meaningful information for policymakers. To derive more realistic estimates of PV potential, geographical and technical constraints (e.g., protected areas, PV module efficiency) are incorporated into the calculation as shown in the following equation (2) [41–45].

(2)

Here, the geographical and technical potential ( in kWh) is calculated from the theoretical potential () in equation (1), while considering regulatory constraints in equation (2). (unitless) is the packing factor, the ratio of the total PV array area to the land area PV arrays occupy. (unitless) is generator-to-system area ratio, which is the ratio of the land area PV arrays occupy (including PV arrays and the spaces between them) to the total suitable land area available for the PV system. It indicates how efficiently the available area is utilized for placing PV systems. It measures how densely the PV arrays are packed within the occupied space. (unitless) is the performance ratio, the ratio of the actual generation achievable in practice to the ideal generation under no-losses conditions. Regardless of module efficiency and shading effect, it measures PV system losses from array temperature, surface soiling, panel degradation etc. is the module efficiency. is the shading factor. As another approach, this study calculates geographical and technical potential using equation (3).

(3)

Here, (in kWh) is annual geographical and technical potential in the individual site ()’s area ( in m2), located within a city& county (), classified as land-use type () and PV technology type (). (in m2) is the area of the individual site. (unitless) is the area factor, which represents the ratio of the land area PV arrays occupy to the total suitable land area available for the PV system. It has the exact same meaning of in equation (2). (in m2/kW) is the density factor, which represents the land area required to install 1kW of PV capacity. It indicates how densely PV systems could be installed in the given area. (unitless) is the capacity factor of a PV system, defined by the ratio of the actual power generation to theoretical power generation if the PV system has generated at its maximum power output during same period [46,47]. There are two different aspects in calculating generation potential between equation (2) and (3). The first one is the measurement of PV installation size: PV array area (in m2) vs. PV capacity (in kW). In some previous studies [42,45,48], the solar radiation utilized by PV array area is measured, represented as in equation. (2). In contrast, other studies [43,49] measure the installed PV capacity, represented as in equation (3). The second difference is the measurement of PV system’s efficiency (%): disaggregation into performance ratio, module efficiency, and shading effect vs. capacity factor as integrated efficiency. In some previous studies [42,43,45,49], energy losses associated with solar-to-electric power conversion and shading effects are divided into three components, represented as in equation (2). In contrast, other studies [50,51] apply a definition-based parameter, the capacity factor, represented as in equation (3). The numerical values for the parameters in Equation (3) (area factor, density factor, and capacity factor) are described in the following sections, with additional details provided in Table 2 and the supplementary data.

* + 1. Area factor: total area to PV system area

Fig. 2 (c) illustrates the graphical concept of the area factor (). Not all of the total area can be utilized for PV system installation due to various constraints. These may include facilities unrelated to PV operation, unsuitable terrain for PV placement, or other factors. The surrounding environment varies significantly across sites, making it impractical to evaluate each site individually. In previous studies, it has been commonly assumed that 70% of the total area is available for PV installation [41,52,53]. However, in this study, area factors are calculated using actual PV installation data or, in some cases, assumed values based on land-use types.

The area factor values vary depending on the type of land use. For industrial complexes, logistics complexes, residential complexes, and public buildings, actual data shows that an average of 54.5% of the total area is utilized for PV system installations. In the case of parking lots, the percentage is much lower, with only 18.9% of the area being used for PV systems. Similarly, for roadside land, 28.4% of the site area is typically utilized for PV installations. For land-use types such as mountainous areas and farmland, where specific data is unavailable, this study assumes that only 5% of the total area can be used for PV systems. This assumption aligns with findings from previous studies [54]. Meanwhile, for floating PV systems, the area factor varies widely in prior research, ranging from 1% to 100% % [55–60]. Based on these findings, this study adopts an assumed area factor of 25% for floating PV installations.

* + 1. Density factor: PV system area to PV capacity

Fig. 2 (d) illustrates the graphical concept of the density factor (), which represents the land area required to install 1 kW of PV capacity. Previous studies have provided different values for density factors based on the type of PV system. For roof-top PV systems, the density factor was estimated as 11.7 m2/kW for single-family buildings, and 4.7 m2/kW for both multi-family and apartment complexes [61]. For ground-mounted PV systems, density factors of 9.57 m2/kW and 13.16 m2/kW were reported in earlier research [62,63]. To improve land-use efficiency, emerging PV technologies such as PV trees [62–64] and agricultural PV [65–67]. have been proposed as alternatives to conventional PV systems. In this study, the density factor values were determined using data from actual PV installation cases. For roof-top PV systems, an average area of 7.23 m2 is required to achieve 1 kW of capacity, while ground-mounted PV systems require 11.50 m2 per kW on average. These observed density factors are applied throughout this research. For floating PV systems, where case data is unavailable, a density factor of 10 m2/kW is assumed based on previous studies [58].

* + 1. Capacity factor: PV capacity to PV generation

Fig. 2 (e) illustrates the graphical concept of the *capacity factor* (), which reflects the ratio of actual PV power generation to its theoretical maximum output. Since PV generation is significantly influenced by weather conditions, it is crucial to apply capacity factors that account for regional weather variations. In this study, capacity factors were applied for 31 cities using electricity market data [68]. Over the past six years, the national average capacity factor for solar PV in South Korea was 14.2%. However, in Gyeonggi Province, the average was slightly lower at 13.6%. Among the cities within Gyeonggi Province, Hwaseong City recorded the highest average capacity factor at 14.9%, while Yangju City had the lowest at 10.8%.

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자동 생성된 설명

Fig. 2. Graphical concept of generation calculation method

* 1. Levelized costs of energy

The levelized cost of electricity (LCOE) is a widely recognized metric for evaluating the economic performance of power generation technologies. It provides a standardized measure of the cost per unit of electricity over the lifetime of a generation system. In South Korea, the Korea Energy Economics Institute (KEEI) conducts comprehensive studies on LCOE, analyzing it by energy source, technology type, and region from a financial perspective [69].

The calculation of LCOE considers various costs incurred over the lifetime of a PV system. These costs include the capital expenditure (), which represents the initial investment required for installing the PV system. Additionally, operating expenditure () accounts for the annual costs of operating and maintaining the system. Another important cost is the interest expense (), reflecting the financial costs associated with borrowing capital for the project. Similarly, the land lease expense () includes the annual costs of leasing land for PV installations. Finally, the calculation incorporates the corporate tax (), representing the taxes applied to the revenues or profits generated by the PV system. These cost components, except for capital expenditure, are annual recurring expenses. To account for their time value, they are discounted using a financial discount rate () and levelized over the system’s operational lifetime (*t*). The LCOE formula is expressed as following equation (4).

(4)

o evaluate the costs of various generation technologies, the levelized cost of electricity (LCOE) is established and widely recognized as a standard metric for the economic assessment of power generation systems. KEEI에서 재생에너지의 원별, 유형별, 지역별 LCOE(발전단가)를 재무적 관점에서 조사하고 있다 LCOE에 포함되는 비용들은 capital expenditure(), operating expenditure(), interest expense(), land lease expense(), corporate tax)이 있다. 한편 분모에 위치한 발전량()은 PV의 degradation rate()을 고려하였다. Capital expenditure를 제외한 나머지 항목들은 매년 발생하는 비용 혹은 편익이므로, 수명기간(t) 동안 재무적 할인율을 적용하여 levelized 하였다[[2]](#footnote-3) (See supplementary material for details).

(4)

해당연구는 국내 지역별로 일사량과 공시지가가 다른 것을 적용하여 전국을 250개 시군구별, PV 유형별 LCOE 분석결과를 공개하였다. 본 연구의 대상지인 경기도는 42개 하위 지역으로 구분되고 (경기도는 31개의 county로 구성되어 있으나, 6개의 county는 town별로도 분석되어 있어서 총 42개의 지역), 동시에 각 지역별로 ground-mounted와 roof-top PV로 나뉘어 LCOE를 분석하였고, which is utilized in this study.

2020년 한국에서 Average LCOE of ground-mounted PV는 규모별로 최소 123.4Won/kWh (20MW 용량급), 최대 152.0Won/kWh (100kW 용량) 인것으로 나타났다. 규모별로 LCOE에 차이가 있는 것은 규모의 경제가 발생하는 것으로부터 비롯한다. 한편 LCOE는 지역별 편차가 더 크게 나타나는데, 이는 지리적요인 (일사량), 규제요인 (개발불가지역), 경제적요인 (지가)의 차이로부터 비롯한다. 경기 지역에서 최소 LCOE는 연천군 지역으로, ground-mounted PV의 경우 146Won/kWh, roof-top PV의 경우 129Won/kWh으로 나타났다. 한편 최대 LCOE는 안양시 동안구로, ground-mounted PV의 경우 1,140Won/kWh, roof-top PV의 경우 1,121Won/kWh 인 것으로 나타났다 (**Supplementary Material**). LCOE 데이터는 우선 GIS-based approach를 통해 태양광 개별적지를 찾아낸 뒤, 개별적지의 위치와 land-use type에 맞도록 LCOE를 매칭하여 활용한다.

* 1. Scenario

경기도 내 31개 city 중 12개 city가 이격거리 규제를 시행 하고 있다. 이격거리 규제의 기준이 되는 장소로는 Residential housing, Roads, Rivers, Tourist attractions, Natural parks, Educational institutions, Medical facilities, Cultural heritage, Historic sites, Public sports facilities, Natural habitation areas이 있다. Residential housing (11개 city), Roads (10개 city), Cultural heritage (6개 city)로부터의 이격거리 규제를 가장 많이 시행하고 있다. Residential housing으로부터의 이격거리는 시군별로 최소 100m, 최대 500m로 규제하고 있고, Roads와 Cultural heritage로부터의 이격거리는 100m~300m로 이격거리를 규제하고 있는 것으로 나타났다. 이격거리 규제에 적용 받고 있는 지역은 아래의 Fig. 3과 같다. 경기도 내 이격거리 규제의 영향을 살펴보기 위해 현재 이격거리 규제를 적용한 시나리오 (Current Setback)와 이격거리 규제를 적용하지 않은 시나리오 (No Setback) 두 가지를 설정하였다.

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Fig. 3. Current status of Setback regulation.

Table. 1. Scenario description

|  |  |
| --- | --- |
| Scenario | Description |
| Current Setback | PV generation potential under current setback regulation |
| No Setback | PV generation potential without Setback regulation |

Table. 2. Assumption for ----

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Land-use type | PV type | Assumed parameters for calculating potential | | | LCOE (Levelized Cost of Energy) |
| Area factor (%) | Density factor (m2/kW) | Capacity factor (%) |
| Industrial complex | Roof-top PV | 54.5 | 7.23 | Applied geographically\*  (It is applied differently depending on the city where the individual site is located.) | |
| Logistics complex |
| Residential complex |
| Public buildings |
| Mountainous area | Ground-mounted PV | 5 | 11.50 |
| Farmland | 5 |
| Parking lot | 18.9 |
| Roadside land | 28.4 |
| Water | Floating PV | 25 | 10 |

1. Results and discussion
   1. Geographical potential of PV

Table. 3은 태양광 잠재량 분석 결과를 i) 태양광 설치가능 면적, ii) 태양광 용량, iii)연간 발전량 측면에서 보여주고 있다. 첫째, 태양광 적지 면적은 Current Setback 시나리오 하에서는 682.45km2으로 나타나고, No Setback 시나리오에서는 78.42% 증가하여 1,217.60 km2 로 나타난다.이는 시나리오별로 각각 경기도 전체 면적 (10,171km2)의 6.7%, 12%에 해당하는 면적이다. 둘째, 태양광 잠재 용량은 Current Setback 시나리오에서는 8.97GW로 나타나고, No Setback 시나리오에서는 38.44% 증가하여 12.41GW로 나타난다. 이는 시나리오별로 각각 2022년까지 경기도에 보급된 태양광 용량 (1.8GW)의 4.98배, 6.89배에 해당하는 용량이다 [6]. 그리고, 경기도의 태양광 보급목표 (9GW) 달성 여부 관련하여, Current Setback 시나리오 (8.97GW)에서는 0.03GW만큼 부족한 것으로 나타나며, No Setback 시나리오 (12.41GW)에서는 충분히 달성 가능 한 것으로 나타난다. 셋째, 태양광 연간 잠재 발전량은 Current Setback 시나리오에서는 10.87TWh로 나타나고, No Setback 시나리오에서는 37.91% 증가하여 15.00TWh로 나타난다. 이는 시나리오별로 각각 2022년 경기도의 전체 전력소비량 (140.6TWh)의 7.8%, 10.7%에 해당하는 발전량이다 [70]. 그리고, 국가 탄소중립 시나리오에서 최소한으로 필요한 태양광 발전량이 449TWh이라고 가정한 것을 상기해보면 (‘Introduction’ 부분 참고), 경기도는 시나리오별로 각각 국가 탄소중립에 필요한 태양광 발전량의 2.4%, 3.3%만큼 기여할 수 있는 것으로 나타난다.

분석결과를 두가지 효율 측면, i) efficiency of land (i.e. area factor and density factor), ii) efficiency of capacity (i.e. capacity factor) 측면에서 살펴보려고 한다. First, (efficiency of land) 경기도 전체적으로 태양광설비가 얼마나 밀집되어 설치될 수 있는지 측면에서 살펴보면, Current Setback 시나리오 하에서는 76.08km2/GW (682.45km2/8.97GW)으로 나타나고, No Setback 시나리오에서는 28.96% 증가하여 98.11km2/GW (1,217.60km2/12.41GW)으로 나타난다. Setback regulation을 해제하면 태양광 설치에 필요한 단위면적이 늘어나는 것인데, 이는 No Setback 시나리오 하에서의 태양광 적지가 Current Setback 시나리오 대비 area factor는 낮고, density factor가 높은 land-use type (ex. Farmland, Mountain)을 많이 포함하고 있음을 의미한다. Table. 3을 보면 Farmland와 Mountain의 면적은 Current Setback 시나리오 대비 No Setback 시나리오에서 각각 96.52%, 87.06%증가하여, 다른 land-use type의 면적 증가율 (ex. Residential: 15.41%)보다 매우 크게 증가함을 볼 수 있다. 같은 맥락에서 Current Setback 시나리오를 기준으로 면적과 발전량을 비교해보면, Roof-top PV 부지 (Residential: 38.70km2, Industrial: 21.76km2, Logistics: 3.15km2, Public: 4.38km2)의 면적은 67.99km2 로서, Ground-mounted PV 부지 (Farmland: 290.60km2, Mountain: 266.59km2, Roadside:6.87km2, Parking: 1.40km2) 면적인 565.46km2보다 매우 작다. 하지만 발전량 측면에서는 roof-top PV부지의 발전량 (Residential: 3.49TWh, Industrial: 2.00 TWh, Logistics: 0.29 TWh, Public: 0.40 TWh)은 6.18TWh로서, Ground-mounted PV 부지의 발전량(Farmland: 1.54TWh, Mountain: 1.44TWh, Roadside: 0.20TWh, Parking: 0.03TWh)인 3.21TWh보다 1.92배만큼 크다. roof-top PV는 ground-mounted PV 대비 활용율이 높고 (area factor is assumed higher), 밀도 있게 설치 (density factor is assumed lower)되기 때문이다. 두번째, (efficiency of capacity) 설치된 용량이 태양광 에너지를 얼만큼 전기에너지로 바꿀 수 있는지 측면에서 살펴보면, Current Setback 시나리오 하에서는 1.212TWh/GW (10.87TWh/8.97GW)으로 나타나고, No Setback 시나리오 하에서는 0.25% 감소하여 1.209TWh/GW (15.00TWh/12.41GW)으로 나타난다. 유의미한 감소라고 보기는 힘들지만, 이러한 경기도 전체의 설비이용률의 감소는 No Setback 시나리오에서 상대적으로 설비이용률이 낮은 지역이 많이 포함된다는 의미다.

Table. 3. Results.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Land-use type | Area (km2, %) | | | Capacity (GW, %) | | | Generation (TWh, %) | | |
| Current Setback | No Setback | Inc (%) | Current Setback | No Setback | Inc (%) | Current Setback | No Setback | Inc (%) |
| Total | 682.45 (100%) | 1217.60  (100%) | 78.42 | 8.97  (100%) | 12.41  (100%) | 38.44 | 10.87  (100%) | 15.00  (100%) | 37.91 |
| Residential | 38.70  (5.67%) | 44.66  (3.67%) | 15.41 | 2.92  (32.54%) | 3.37  (27.12%) | 15.41 | 3.49  (32.14%) | 4.02  (26.83%) | 15.13 |
| Industrial | 21.76  (3.19%) | 25.29  (2.08%) | 16.24 | 1.64  (18.30%) | 1.91  (15.36%) | 16.24 | 2.00  (18.41%) | 2.33  (15.56%) | 16.52 |
| Logistics | 3.15  (0.46%) | 5.45  (0.45%) | 72.87 | 0.24  (2.65%) | 0.41  (3.31%) | 72.87 | 0.29  (2.62%) | 0.49  (3.28%) | 72.70 |
| Public | 4.38  (0.64%) | 5.62  (0.46%) | 28.33 | 0.33  (3.68%) | 0.42  (3.41%) | 28.33 | 0.40  (3.64%) | 0.51  (3.39%) | 28.20 |
| Farmland | 290.60  (42.58%) | 571.08  (46.90%) | 96.52 | 1.26  (14.09%) | 2.48  (20.01%) | 96.52 | 1.54  (14.17%) | 2.99  (19.91%) | 93.67 |
| Mountain | 266.59  (39.06%) | 498.68  (40.96%) | 87.06 | 1.16  (12.93%) | 2.17  (17.47%) | 87.06 | 1.44  (13.20%) | 2.65  (17.69%) | 84.81 |
| Roadside | 6.87  (1.01%) | 8.74  (0.72%) | 27.33 | 0.17  (1.89%) | 0.22  (1.74%) | 27.33 | 0.20  (1.88%) | 0.26  (1.74%) | 27.07 |
| Parking | 1.40  (0.21%) | 1.70  (0.14%) | 21.39 | 0.02  (0.26%) | 0.03  (0.23%) | 21.39 | 0.028  (0.25%) | 0.034  (0.22%) | 21.45 |
| Water | 49.00  (7.18%) | 56.37  (4.63%) | 15.04 | 1.23  (13.67%) | 1.41  (11.35%) | 15.04 | 1.49  (13.67%) | 1.71  (11.38%) | 14.86 |
| \* The numbers (%) in parentheses indicate the proportion of the total value. | | | | | | | | | |

아래 Fig. 4는 이격거리 규제가 없어졌을 때, 늘어나는 잠재발전량을 Land-use type별로 보여주고 있다. (See Table. 3 for detail values)

**Residential)** 경기도는 국가 전체면적의 10.2%만 차지하고 있지만, 국가 전체 인구의 27.4%가 살고 있는 지역이다. 그 만큼 residential 건물이 많이 있음을 의미하고, Fig에서도 확인할 수 있듯이, current setback과 no setback 시나리오 모두에서 잠재 발전량이 가장 높은 Land-use type인 것으로 나타났다. Current Setback 시나리오에서의 잠재 발전량은 3.49TWh으로 나타났고, No setback 시나리오에서는 15.19% 증가하여, 4.02TWh으로 나타난다. 이는 시나리오 각각에 대해 2021년 경기도 가정부문 전력소비량 (21.13TWh)의 16.52%, 19.03% 만큼과 같은 양이다.

**(Industrial, Logistics)** Industrial과 Logistics의 잠재 발전량 RE100 달성 차원에서 중요한 부분이다. 기업들이 RE100 달성 수단으로 (어떤이유로?) 비계통연계형 PPA를 선호(source)하는 점을 고려할 때, 사업장 옥상에 바로 설치하여 자가소비를 하는 것이 유리하기 때문이다. Industrial의 경우, Current Setback 시나리오에서의 잠재 발전량은 2.00TWh으로 나타났고, No Setback 시나리오에서는 16.52% 증가하여 2.33TWh로 나타난다. Logistics의 경우, Current Setback 시나리오에서의 잠재 발전량은 0.29TWh로 나타났고, No Setback 시나리오에서는 72.70% 증가하여 0.49TWh로 나타났다. Industrial과 Logistic의 발전 잠재량을 합쳐 보면, 시나리오 각각에 대해 2022년 산업부문 전력소비량 (74.07TWh)의 3.09%, 3.81% 만큼과 같은 양이다.

**(Farmland, Mountain)** Setback regulation 해제로 인해 잠재 발전량이 가장 많이 늘어나는 Land-use type이 Farmland와 Mountain으로 나타났다. Farmland의 경우, Current Setback 시나리오에서의 잠재 발전량은 1.54TWh으로 나타났고, No Setback 시나리오에서는 93.67% 증가하여, 2.99TWh로 나타난다. Mountain의 경우, Current Setback 시나리오에서의 잠재 발전량은 1.44TWh로 나타났고, No Setback 시나리오에서는 84.81% 증가하여 2.65TWh로 나타난다. Farmland와 Mountain 부지에 태양광을 설치하는 경우에는 horticultural에 대한 염려를 해결하는 것이 필수과제이다 (source). Farmland의 태양광 보급을 장려하기 위해서는 농작물 생산과 태양광 발전을 동시에 가능케하는 Agro PV에 대한 경제적 편익을 강조하는 것이 필요하다. Mountain의 태양광 보급을 장려하기 위해서는 생태계 보존과 조화를 이루어 green on green conflict를 잘 다루는 것이 관건이다. 태양광이 온실가스 감축측면에서는 긍정적인 효과가 있지만, 한편으로는 온실가스 흡수, 생태계 보전 측면에서는 부정적인 측면을 갖고 있기 때문이다 [71,72].

**(Water)** 인구밀도가 높은 국내 상황을 고려할 때, 수면을 활용한 태양광 설치는 온실가스 감축을 위해 꼭 필요한 전략 중 하나이다. Current Setback 시나리오에서의 잠재 발전량은 1.49TWh으로 나타났고, No setback 시나리오에서는 14.86% 증가하여, 1.71TWh으로 나타난다. Setback regulation 해제로 인한 잠재량 증가가 가장 작게 나타나는 land-use type이다. 물이 고여 있어야 하는 reservoirs, lakes, dams의 특성상, 도심지 시설 중심으로 설정되는 이격거리 규제에 영향을 많이 받지 않는 것으로 나타난다. 다만 Farmland, Mountain 부지의 태양광과 마찬가지로 horticultural에 대한 염려와 생태계에 부정적인 영향이 고려되어야 한다. Water-surface photovoltaic (WSPV) [[3]](#footnote-4) systems reduce water temperature, dissolved oxygen, and uncovered surface area, harming plankton diversity and bird communities [73].

**(Public)** Public buildings은 정부가 소유 및 운영하고 있기 때문에, 정부 정책 의지에 따라 태양광 보급을 적극적으로 실현할 수 있는 land-use type이다. Current Setback 시나리오에서의 잠재 발전량은 0.40TWh으로 나타났고, No setback 시나리오에서는 28.20% 증가하여, 0.51TWh으로 나타난다. 이는 시나리오 각각에 대해 2022년 경기도 Public부문 전력소비량(10.01TWh)의 4.00%, 5.10% 만큼과 같은 양이다. 다른 부문에 비교적 태양광 도입의 수용성이 높은 만큼, 정부가 나서서 가장 먼저 태양광 보급 도입 추진을 고려할 수 있는 land-use type이다.

**(Roadside)** 토지 이용이 어떤 목적으로도 활용되고 있지 않고 있다는 점과 도로 주변의 토지인 바, 도로공사 소유라는 점이라는 태양광 도입을 위한 긍정적인 측면을 갖고 있다. 따라서 Public 부문과 마찬가지로 수용성이 높은 곳으로 판단된다. Current Setback 시나리오에서의 잠재 발전량은 0.20TWh으로 나타났고, No setback 시나리오에서는 27.07% 증가하여, 0.26TWh으로 나타난다.

**(Parking)** 시나리오에 상관없이 잠재 발전량이 가장 적은 land-use type으로 나타난다. Current Setback 시나리오에서의 잠재 발전량은 0.028TWh으로 나타났고, No setback 시나리오에서는 21.45% 증가하여, 0.034TWh으로 나타난다. 주차장 부문은 ground-mounted PV 설치대상으로 분류되는 land-use type (Farmland, Mountain, Roadside) 중에서 Farmland와 함께 기존의 토지 이용 목적 (i.e. parking)을 달성하면서 동시에 태양광을 설치할 수 있는 land-use type이다.

텍스트, 스크린샷, 도표, 직사각형이(가) 표시된 사진

자동 생성된 설명

Fig. 4. PV generation potential by land use type

텍스트, 지도, 폰트, 그래픽 디자인이(가) 표시된 사진

자동 생성된 설명

Fig. 5. Spatial distribution of PV generation potential

* 1. Supply curve of PV

개별부지별 태양광 적지에 지역별 유형별 LCOE (SeeMethod section)를 적용하면 아래 Fig. 6와 같이 geospatial supply curve를 도출해낼 수 있다. f점과 m점 사이의 bar chart들의 윗 선분을 이으면 Current setback 시나리오에서의 PV 공급곡선이고, f점과 n점 사이의 bar chart들의 윗 선분을 이으면 No setback 시나리오에서의 PV 공급곡선이다. 공급곡선을 토대로, 3가지 deployment strategy를 수립할 수 있다: i) price-based strategy, ii) quantity-based strategy, iii) full deployment이다 (Table. 4). 첫번째 price-based strategy는 SMP보다 낮은 LCOE를 갖는 개별부지 (시장 잠재량)에 태양광을 우선 보급하는 전략으로서, Fig. 6에서 SMP in 2023 ,(g) horizontal line in Fig. 6, 보다 아래에 위치한 bar들의 보급을 의미한다. 두번째, quantity-based strategy는 경기도에서 목표로하고 있는 9GW를 우선 보급하는 전략으로서, Fig. 6에서 (cl) line (9GW에서 예상되는 연발전량)의 왼쪽에 위치한 bar들의 보급을 의미한다. 세번째, full deployment strategy는 적지로 분석된 모든 부지에 태양광을 보급하는 전략이다. Full deployment strategy에서 Current setback 시나리오의 경우, Fig. 6의 (dm)line의 왼편, No setback 시나리오의 경우, Fig. 6의 (en) line의 왼편에 위치한 bar들을 의미한다.

3가지 전략에 대해서 다음의 3가지 측면을 살펴보고자 한다 (Table. 4): i) generation, ii) avoided emissions, iii) generation costs, iv) average costs of generation and avoided emissions (table의 종축). 첫번째 측면, generation을 살펴보면, price-based strategy에서 Current setback 시나리오에서 잠재발전량은 1.55TWh (line oa)로 가장 작았고, No Setback 시나리오에서는 161% 증가 (2.49TWh) 하여 4.04TWh (line ob)으로 나타났다. Price-based strategy의 경우, 두 시나리오 모두 Quantity target (line oc)은 달성하지 못하는 것으로 나타난다. Quantity-based strategy는 target이 quantity이므로, 시나리오들의 발전량은 10.72TWh로 같다. Full deployment strategy는 앞 절에서 살펴본 대로, Current setback 시나리오에서 발전잠재량은 10.87TWh (line od)으로 나타났고, No Setback 시나리오에서는 37.91% 증가 (4.13TWh)하여 15.00TWh (line oe)의 발전 잠재량이 있는 것으로 나타났다. 이격거리 규제가 발전량에 미치는 영향을 전략별로 살펴보면, 발전량의 변화량 측면에서는 Full deployment strategy가 Price-based strategy보다 이격거리 규제에 의한 영향(4.13TWh vs. 2.49TWh)을 많이 받는 것으로 나타나지만, 발전량의 변화율 측면에서는 Price-based strategy가 Full deployment보다 영향을 많이 받는 것으로 나타났다 (160.65% vs. 37.91%). 한편 시나리오를 기준으로 전략을 살펴보면, 이격거리가 있을 때는 전체 잠재발전량(10.87TWh) 중 경제성이 확보된 잠재량 (1.55TWh)의 비중은 14.26% (line oa/od)인데 반해, 이격거리가 없을 때는 그 비중이 26.93% (4.04/15.00) (line ob/oe)로 증가한다.

두번째 측면, avoided emissions란 태양광 발전량만큼, 다른 화석 에너지원을 활용하여 발전을 하지 않아도 되기 때문에, 온실가스 배출을 회피할 수 있다는 뜻이다. 계산방법은 발전량에 전력배출계수(0.4434 tCO2/MWh)를 곱하였으므로, 발전량과 비례한다 [74]. Price-based strategy의 경우, Current Setback 시나리오에서 avoided emissions은 0.69MtCO2으로 나타났고, No Setback 시나리오에서는 1.10MtCO2 증가하여, 1.79MtCO2 나타났다. Quantity-based strategy의 경우 시나리오간 차이가 없다. Full deployment strategy의 경우, Current Setback 시나리오에서 avoided emissions은 4.82MtCO2으로 나타났고, No Setback 시나리오에서는 1.83MtCO2 증가하여, 6.65MtCO2 나타났다. 이는 시나리오 각각에 대해 2021년 경기도 온실가스 배출량 (87.74MtCO2)의 5.49%, 7.58% 만큼과 같은 양이다.

세번째 측면, Generation costs는 연간 발전에 소요되는 비용을 의미하며, 발전량과 LCOE의 곱으로 계산한다. 발전량이 늘어날수록 그 비용 또한 같이 증가한다. Quantity-based strategy에서 Current setback 시나리오의 경우, 2,808.7 Million USD의 비용이 소요되고, No setback 시나리오의 경우, 1,609.4 Million USD의 비용이 소요되는 것으로 나타났다. 같은 양(10.72TWh)의 태양광 발전량을 공급하는데, 이격거리 규제를 해제하는 경우, 현재 대비 42.7%의 비용 절감을 할 수 있는 것으로 나타났다. 각 전략별로 소요되는 비용의 크기는 Fig. 6에서 면적으로 표시가 가능하며, Table. 4의 (C) column에 표시해놓았다.

넷째, 편익과 비용을 동시에 고려하기 위해서 단위비용을 살펴보아야 한다. Average costs of generation과 Average costs of avoided emissions 측면에서 단위비용이 가장 낮은 전략은 Price-based strategy의 No Setback 시나리오 (121.7USD/MWh, 274.4USD/tCO2 respectively)인 것으로 나타났다. Price-based strategy의 경우, Current Setback 시나리오에서 발전 단위당 비용이 124.3 USD/MWh으로 나타났고, No Setback 시나리오에서는 2.09% 감소하여 121.7USD/MWh으로 나타난다. Quantity-based strategy의 경우, Current Setback 시나리오에서 발전 단위당 비용이 261.9USD/MWh으로 나타났고, No Setback 시나리오에서는 42.69% 감소하여 150.1USD/MWh으로 나타난다. Full deployment strategy의 경우, Current Setback 시나리오에서 발전 단위당 비용이 270.4USD/MWh으로 나타났고, No Setback 시나리오에서는 14.68% 감소하여 230.7USD/MWh으로 나타난다. 태양광 도입 전략별로 Setback regulation 해제가 발전 단위비용의 감소율 미치는 영향은 Quantity-based strategy (42.69%), Full deployment (14.68%), price-based strategy (2.09%) 순으로 크게 나타났다. 이와 같은 Setback regulation 해제에 따른 전략별 감축 단위비용의 감소율은 발전 단위비용의 감소율 결과와 똑같다.

Table. 4. Summary table

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Deployment strategy | | Scenario | Generation  (TWh) | Avoided emissions  (MtCO2) | Generation costs  (Million USD) | Average costs of  generation  (USD/MWh) | Average costs of  avoided emissions  (USD/tCO2) |
| (A) | (B) | (C) | (C/A) | (C/B) |
| Strategic  deployment | Price-based  strategy | Current  Setback | 1.55  (oa) | 0.69 | 192.6  (oahf) | 124.3 | 280.3 |
| No  Setback | 4.04  (ob) | 1.79 | 491.2  (obif) | 121.7 | 274.4 |
| Quantity-based strategy | Current  Setback | 10.72  (oc) | 4.75 | 2,808.7  (oclf) | 261.9 | 590.8 |
| No  Setback | 10.72  (od) | 4.75 | 1,609.4  (ockf) | 150.1 | 338.5 |
| Full  deployment | | Current  Setback | 10.87  (oe) | 4.82 | 2,940.2  (odmf) | 270.4 | 609.8 |
| No  Setback | 15.00  (oe) | 6.65 | 3,459.5  (oenf) | 230.7 | 520.3 |

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Fig. 6. Geospatial supply curve of PV generation

1. Conclusions and policy implications

본 연구는 한국의 17개 시도 중에 인구가 가장 많고, 또 전력소비량이 가장 많은 지역인 경기도를 대상으로 아래와 같이 연구를 진행하였다. GIS tool을 활용하여, 경기도 내 태양광 적지를 land-use type별 개별부지 단위로 조사하였다. 태양광 설치 실사례 데이터를 토대로 Land-use type별 특성에 따라 Area factor, Density factor, Capacity factor를 계산하여, 이를 개별부지별 잠재용량과 잠재 발전량 계산에 활용하였다. 나아가 개별부지의 위치와 PV 유형에 따라 LCOE데이터를 적용하여, 개별부지 단위로 geospatial supply curve of PV generation을 도출하였다. 도출한 공급곡선을 통해 3가지 전략을 세운 뒤 전략별 benefits (i.e. generation, avoided emissions)과 costs를 분석하였다.

Setback regulation을 해제한다면, 현재 Setback regulation을 유지하는 경우에 대비해서 태양광 설치가능 면적은 78.42%, 용량은 38.44%, 발전량은 37.91% 만큼 증가하는 것으로 나타난다. 이처럼 Setback regulation 해제 시 잠재량이 늘어나기는 하지만 주어진 자원을 얼마나 효율적으로 활용하게 되는지에 대한 변화를 살펴볼 필요가 있다. 토지를 얼마나 집약적으로 사용하는지 (area factor, density factor), 또 태양광 설비가 얼마나 많은 전력을 생산하는지 (capacity factor) 단위당 평가를 통해 태양광 보급의 효율성 측면에서 평가를 진행하였다. First, Setback regulation 해제 시 Area factor는 낮고, Density factor는 높은 Farmland와 Mountain land-type의 면적이 대폭 늘어, 토지 면적당 설치 가능한 태양광 용량이 떨어져, 토지 활용의 효율성이 감소하였다. 이는 Setback regulation 해제 시, 토지사용의 효율성이 감소할 수 있고, 또 Farmland와 Mountain부지의 특성상 환경에 부정적인 영향을 초래하는 결과가 나타날 수 있음을 의미한다. 이처럼 Land-use type별 토지 효율의 차이에 따라 의도치 않은 결과가 발생할 수 있음을 고려할 때, 모든 유형에 동일한 규제를 적용하기보다는 효율성을 반영한 차별화된 규제나 인센티브 정책이 필요함을 시사한다. Setback regulation 해제에 따른 설비의 효율성 (capacity factor)도 약간 감소 (0.25%)하는 것으로 나타난다. 위와 같이 Setback regulation을 완화하면 태양광 발전 잠재량은 증가하지만, 효율성 측면에서 그 의미가 희석될 가능성이 있다. Setback regulation 해제 이후에도 이전과 같은 효율성을 유지하기 위해서는 roof-top PV의 보급을 늘릴 수 있는 방안을 고려해보는 것이 필요하다.

Setback regulation의 유/무에 상관없이 Residential 부문의 태양광 잠재량이 가장 많은 비중을 차지하는 것으로 나타났다. 따라서 정책적으로 건물 옥상 태양광 설치 지원 정책은 초기에 태양광 보급의 빠른 증가를 유도해낼 수 있는 수단이 될 수 있다. 특히 정부에서는 자가소비용 태양광이 직접 전력을 생산 및 사용을 함에도 불구하고 REC 발급이 불가능했는데, 자가 소비용 태양광에 대한 REC 도입을 공식화하고 내년부터 본격 추진할 계획이다. 이러한 정책은 자가 소비용 태양광이 많은 Residential 부문의 신규 태양광 도입을 촉진할 수 있는 중요한 정책으로 보인다. Industrial과 logistics 부문의 태양광 발전 잠재량은 기업에게 RE100 달성수단으로 중요한 전략 중 하나이다. 최근 국내에서는 분산에너지시스템 활성화를 위해 지역별 전력자급률에 근거로 하여 전력요금 차등화 방안을 논의하고 있다. 전력자급률이 낮은 경기도에 위치한 기업들은 전력요금 상승 위험으로 인한 경제적 타격을 받을 것으로 예상된다. 따라서 Industrial과 logistics 부문의 태양광 도입은 경기도 내 기업들의 RE100 달성과 비용절감이라는 두 가지 측면에서 도움이 될 수 있는 효율적인 수단이다. Farmland, Mountain, Water 부문은 환경에 대한 부정적 영향을 최소화하여 태양광 도입을 추진하는 전략이 필요하다. Public과 Roadside의 경우 정부가 소유 및 운영하고 있는 land-use type으로서 정책적 의지가 있으면 비교적 손쉽게 태양광이 보급될 수 있는 장점이 있다.

Geospatial supply curve of PV generation을 통해 경기도가 추진할 수 있는 태양광 보급 전략을 3가지(Price-based, Quantity-based, Full deployment)로 나누어 benefits (generation, avoided emissions) & costs를 평가해보았다. 경제성이 확보되는 태양광을 전부 설치하더라도, 경기도의 태양광 보급목표치를 달성하지 못하는 것으로 나타났다. 이는 경제성을 갖춘 태양광만을 통해서는 양적 목표를 달성할 수 없음을 의미하고, 따라서 태양광 보급 목표 달성을 위해서는 정부의 보다 적극적인 경제적 유인 정책이 필요한 것으로 나타났다. Price-based strategy는 Setback regulation 해제에 따라 발전 잠재량 증가율이 가장 높은 전략으로 나타났다. 이는 국가 탄소중립 목표 대비 아직 태양광 시장이 초기 단계임을 고려할 때, price-based strategy는 초기에 효율적으로 태양광 보급을 빠르게 늘릴 수 있는 전략임을 시사한다. 이와 같은 사실을 반대로 해석을 해보면, Setback regulation에 의해 발전량 감소율이 가장 큰 전략이 Price-based strategy으로 나타난 것이고, 이는 이격거리 규제가 단순히 물리적 공간의 제한을 넘어서, 경제적 타당성 제약으로 더 크게 작용할 수 있음을 의미한다.

Setback regulation이 있는 경우, 전체 발전 잠재량 중에 경제성이 확보된 비중은 14.26%인데, Setback regulation이 해제되는 경우, 그 비중이 26.93%으로 증가하는 것으로 나타난다. 이는 Setback regulation 해제가 태양광 도입의 기술적 가능성을 경제적 타당성으로 까지 확장될 수 있는 확률이 높아짐을 의미한다. Setback regulation 해제시, 경제성이 확보된 부지의 비중이 증가하여 태양광 발전의 평균 수익성이 향상될 가능성이 높아진 것이다. 이는 3가지 전략 모두에 대해, Setback regulation 해제에 따라 발전 단위당 비용이 감소한 것과 맥락을 같이한다. Setback regulation 유/무와 관계없이 발전단위당 비용이 낮은 전략은 price-based, quantity-based, full deployment strategy 순이었다. 한편 Setback regulation 해제에 따른 단위비용 절감율 효과가 큰 전략은 Quantity-based, Full deployment, price-based strategy 순이었다. price-based strategy는 높은 비용 효율성을 유지할 수 있음을 의미하지만, price-based strategy가 상대적으로 Setback regulation 해제로부터 받는 영향이 제한적임을 의미한다. 이는 price-based strategy가 태양광 보급량 확대 보다는 비용 절감을 우선시하는 전략이기 때문이다. Quantity-based strategy는 발전단위당 비용이 2번째로 높은 전략이었지만, Setback regulation 해제로 인해 보급 가능한 태양광 설비가 크게 늘어나면서 비용효율성을 극대화할 수 있는 전략으로 나타난다. Full deployment strategy는 낮은 비용 효율성을 보이고, 또 Setback regulation 해제 후에도 비용 절감율 효과가 제한적으로 나타나지만, 태양광 보급량 확대에 가장 유리한 전략이다. 이는 최대한 많은 부지에 태양광 보급을 하고자 하는 전략의 특성상 경제성이 낮은 부지도 다수 포함되어 있기 때문이다.

전략별 특성에 따라 예상되는 효과가 다르게 나타나면서, 종합적으로 살펴보면 이격거리 해제는 태양광 발전 비용 효율성을 전반적으로 개선하는 것으로 나타난다. Setback regulation 유/무에 따른 전략 선택은 비용 효율성과 보급 목표를 고려한 정책적 균형이 중요할 것으로 보인다. 단기적으로는 price-based strategy, 중기적으로는 Quantity-based strategy를 중심으로 하는 혼합 접근법이 효과적일 수 있다. 장기적 차원에서는 국가 탄소중립과 같은 보다 큰 목표 달성을 위해 Full deployment strategy를 고려해볼 필요가 있다. Setback regulation을 해제하고, Full deployment strategy전략을 선택하는 경우 6.65 MtCO2 만큼의 온실가스 감축효과가 있는 것으로 나타났다. 이는 2021년 국가 온실가스 배출량의 1%, 경기도 온실가스 배출량의 7.6%에 해당하는 양을 감축하는 효과와 같다.

본 연구에서 활용된 LCOE(Levelized Cost of Electricity) 데이터에는 일부 중요한 비용 항목들이 반영되지 않았다는 점에서 한계가 있다. 선행연구에서는 LCOE를 크게 Plant Performance, Investment-Related Cost, Operation-Related Cost, Risk & Uncertainty의 네 가지 측면에서 분류하고 있다[75]. 그러나 본 연구의 LCOE 데이터에는 다음과 같은 두 가지 주요 측면이 충분히 고려되지 않았다.

첫째, 간헐성으로 인해 발생하는 비용이 포함되지 않았다. 태양광 발전의 특성상 간헐성(intermittency)으로 인해 전력망 통합에 필요한 추가 비용, 예비력 확보 비용, 주파수 및 전압 조정 비용과 같은 Integration Cost와 Ancillary Service Cost가 발생한다. 이러한 비용은 태양광 발전이 기존 전력망과 융합되는 과정에서 시스템 전반의 안정성과 효율성을 유지하기 위해 고려되어야 하지만, 본 연구의 LCOE 데이터에는 반영되지 않았다.

둘째, 정부 보조금이나 정책적 지원의 영향을 배제하고 분석이 이루어진 점도 한계로 지적될 수 있다. 실제 태양광 발전 프로젝트는 다양한 형태의 보조금, 세제 혜택, 재정 지원 등으로 경제성이 크게 달라질 수 있다. 이로 인해 실제 태양광 발전 사업자가 체감하는 경제성을 반영하지 못하지만, 보조금 또한 정부가 지출하는 비용이기 때문에 사회 전체적인 비용측면에서는 동일하다고 할 수 있다.

**CRediT authorship contribution statement**

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**Declaration of competing interest**

The authors declare that they have no know competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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2. The discount rate is applied to electricity generation in the formula not to discount the physical output itself, but to account for the time value of the economic revenue generated from that output, as revenue today holds greater value than revenue in the future. [↑](#footnote-ref-3)
3. Water-surface photovoltaic (WSPV) systems are categorized into floating photovoltaic systems (FPVs), where PV panels are installed on floating materials atop the water surface, and pile-mounted photovoltaic systems (PMPVs), where PV panels are fixed onto piles rather than floating. [↑](#footnote-ref-4)