The impact of setback regulations on PV deployment strategies in Gyeonggi province, South Korea

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Abstract

This study investigates the impact of setback regulations on photovoltaic (PV) deployment in Gyeonggi Province, South Korea, a region with high renewable energy demand. Using GIS-based spatial analysis, PV-suitable sites were identified and analyzed under current and no setback scenarios. Observed PV data informed calculations for PV generation potential and economic viability. Removing setback regulations increases PV installation area by 78.42%, capacity by 38.44%, and generation potential by 37.91%. However, this expansion reduces efficiency, especially in farmland and mountainous areas. Agrophotovoltaic and eco-conscious strategies are suggested to address environmental concerns. The residential sector offers the highest potential, highlighting the value of rooftop PV policies. Three deployment strategies were evaluated: price-based, quantity-based, and full deployment. The price-based strategy is cost-efficient but falls short of targets. The full deployment strategy meets PV goals but at higher costs. The quantity-based strategy balances scalability and cost-efficiency, reducing costs by 42.7% without setback regulations. This study underscores the importance of tailored policies to enhance PV deployment in densely populated, land-constrained areas, offering insights for achieving renewable energy targets.

Keywords: PV potential, PV deployment strategy, Setback regulation, GIS analysis, Supply curve of PV generation

1. Introduction

As the 13th largest greenhouse gas emitter, South Korea accounted for 1.3% of global greenhouse gas emissions [1]. The country has pledged to achieve its nationally determined contribution 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]. In South Korea, all solar energy-based power generation relies exclusively on photovoltaic (PV) technology, with no contribution from solar thermal technology. 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%. 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[7], 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'. South Korea's PV potential was estimated at 137,347 TWh/year, 3,117 TWh/year, and 495 TWh/year for theoretical, geographical & technical, and economic potential [8], respectively, based on categorization of PV potential from previous studies [9–11]. 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 [12]. While energy policies can promote renewable energy expansions by internalizing its positive externalities [13,14], 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 [15–19]. 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 [20]. Local residents often resist PV facilities due to concerns about environmental degradation and visual impacts [21–24]. Although efforts such as sharing economic benefits from PV projects [25–28], involving residents in the development process [29], and building trust in PV systems [30] 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

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on PV, which accounts for 61% of its renewable energy generation, and (ii) its limited land availability. Furthermore, South Korea ranks 22nd globally in population density, with 530 people per km^2 among 216 countries [31]. These factors make it challenging to identify suitable sites that meet all the conditions for installing PV facilities, highlighting the urgent need to better understand the effects of setback regulations. Previous studies have investigated the effects of setback regulations on PV deployment potential, primarily at national or provincial scales. For example, they indicate that under nationwide setback regulations, only 23% of geographic & technical 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 [32]. In Incheon province, which has 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 [33]. 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 [34]. While previous research has provided valuable insights at broader scales, few studies have systematically incorporated setback regulations into land-use differentiated geospatial supply curves at a granular plot level. This study addresses this gap by integrating detailed setback regulations and observed PV installation data into a fine-scale spatial analysis, differentiated by land-use types. By constructing geospatial supply curves across multiple land-use categories, the study provides a more comprehensive understanding of PV deployment strategies under varying regulatory conditions.

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 (see Supplementary Materials for details). These regulations primarily pertain to minimum distances from residential areas and roads, with setback distances ranging from 100 meters to 500 meters. Gyeonggi Province accounts for 10.2% of South Korea's total area [35] and is home to 27% of the population [36]. It is the region where the introduction of renewable energy is most urgently needed among South Korea's 17 provinces [37]. First, a regionally differentiated 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% [38], 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 [39,40]. Providing these companies with locally produced renewable energy (e.g., through a power purchase agreement) will help them achieve their RE100 goals and mitigate economic losses. Third, the governor of Gyeonggi Province is committed to expanding PV [41]. 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 PV during his term. In this context, the expansion of PV facilities in Gyeonggi Province is crucial.

This study follows the methodology outlined in Fig. 1. First, PV-eligible individual plots in Gyeonggi Province are categorized into nine land-use types. Using GIS tools, suitable plots are identified by excluding currently installed PV sites, mountains with slopes exceeding 15 degrees, and legally protected farmland and mountainous areas. Area factors, density factors, and capacity factors are applied to estimate the annual generation potential of these plots. To evaluate economic viability, levelized cost of electricity (LCOE) data from external sources are incorporated to derive the geospatial supply curve of PV generation. Based on this analysis, three deployment strategies—quantity-based, price-based, and full deployment—are proposed and assessed for their impact on generation, greenhouse gas reductions, and costs under different setback regulation scenarios.

Building on prior research that emphasizes geospatial supply curves, this study advances the field by integrating deployment strategies and deriving their policy-relevant implications. Geographic & technical, and economic potential conditions are combined with scenario-based setback regulations to provide a comprehensive perspective on PV deployment. The incorporation of observed data from actual PV installations enhances the accuracy of the estimated generation potential. Furthermore, the analysis evaluates generation capacity, greenhouse gas reductions, and cost-efficiency, offering a well-rounded assessment of PV deployment strategies. This comprehensive approach bridges regulatory frameworks with the critical need for renewable energy expansion in densely populated and land-constrained regions like Gyeonggi Province. It delivers actionable insights for policymakers aiming to optimize PV deployment in such challenging contexts.

This study addresses the following research questions: i) How do setback regulations affect the deployment potential and economic feasibility of PV systems in land-constrained regions? ii) What are the trade-offs between maximizing installation area and maintaining deployment efficiency? iii) What are the optimal deployment strategies under different setback regulation scenarios?

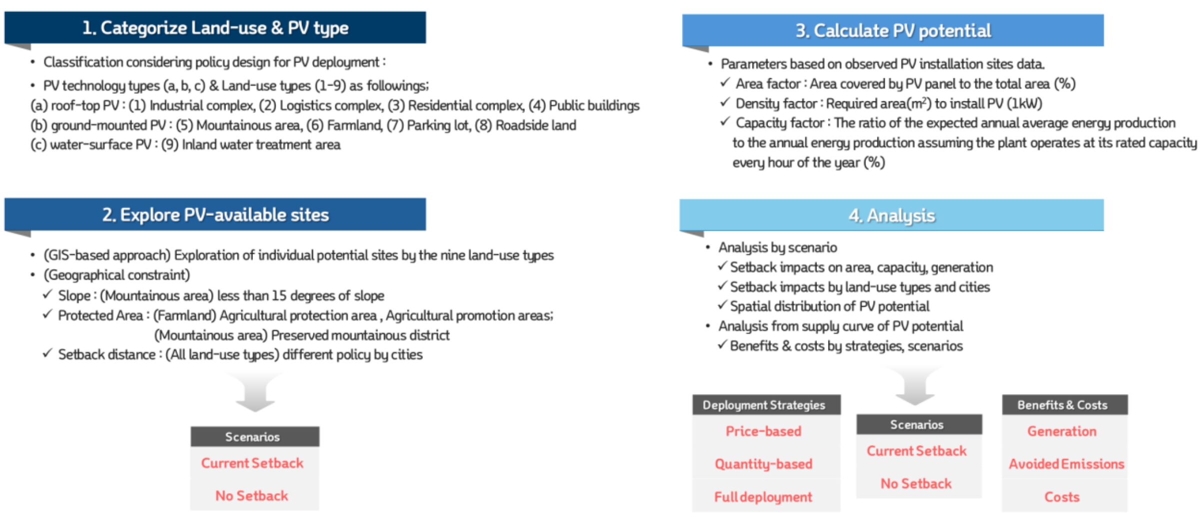

Fig. 1. Study flow of this study

2. Methodology

2.1 Site categorization

This study utilized GIS tools to investigate PV-eligible sites in Gyoenggi province, categorized into nine land-use types. Land-use types exhibit distinct socioeconomic and physical characteristics. For example, from a legal perspective, governments establish management and planning regulations for each land-use type. From an economic perspective, cases like agrophotovoltaic (AgroPV) emphasize balancing agricultural revenue with income from PV generation, whereas in commercial areas, potential restrictions on business activities (e.g., parking space or roof-top 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, the physical differences among land-use types are notable. For example, mountainous areas might have higher 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 PV deployment policies tailored to specific land-use types [42–44]. Reflecting these distinctions, this study categorizes PV-eligible sites by land-use types as follows to support the development of effective policies:

- 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). The term ‘Industrial’ will be used to refer to ‘Industrial complex’ hereafter.
- 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). The term ‘Logistics’ will be used to refer to ‘Logistics complex’ hereafter.
- 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). The term ‘Residential’ will be used to refer to ‘Residential complex’ hereafter.
- 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. The term ‘Public’ will be used to refer to ‘Public building’ hereafter.
- 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). The term ‘Mountain’ will be used to refer to ‘Mountainous area’ hereafter.
- 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). The term ‘Parking’ will be used to refer to ‘Parking lot’ hereafter.
- Roadside land: unused spaces between roads and road facilities, often managed as green spaces by the Korea Expressway Corporation. (ex. interchanges, junctions, and 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). The term ‘Water’ will be used to refer to ‘Inland water treatment area’ hereafter.

2.1.1 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 are 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 Setback regulation scenario section.

2.2 Calculation of PV potential

The annual (8,760 hours) theoretical potential generation (g^T in kWh) of PV in a given site (i) with area (a in m^2) can be calculated based on the global horizontal irradiation (I in kW/m^2) using the following equation (1).

$$g^T = a_i \times I_i \times 8760 \tag{1}$$

However, the theoretical potential has limitations in providing meaningful information for policymakers. To derive more realistic estimates of PV potential, geographic & technical constraints (e.g., protected areas, PV module efficiency) are incorporated into the calculation as shown in the following equation (2) [45–49].

$$g^{GT} = a_i \times I_i \times 8760 \times PF \times GSR \times PR \times \eta \times (1 - F_s) \tag{2}$$

Here, the geographic & technical potential (g^{GT} in kWh) is calculated from the theoretical potential (g^T) in equation (1), while considering geographic and technical constraints in equation (2). PF (unitless) is the packing factor, the ratio of the total PV array area to the land area PV arrays occupy. It measures how densely the PV arrays are packed within the occupied space. GSR (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. PR (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. η is the module efficiency. F_s is the shading factor. As another approach, this study calculates geographic & technical potential using equation (3).

$$g^{GT} = a_{i,j,l,k} \times AF_l \times DF_k^{-1} \times CF_j \times 8760 \quad (3)$$

Here, g^{GT} (in kWh) is annual geographical & technical potential in the individual site (i)'s area (a in m^2), located within a city& county (j), classified as land-use type (l) and PV technology type (k). $a_{i,j,l,k}$ (in m^2) is the area of the individual site. AF_l (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 GSR in equation (2). DF_k (in m^2/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. CF_j(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 [50,51]. 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 m^2) vs. PV capacity (in kW). In some previous studies [46,49,52], the solar radiation utilized by PV array area is measured, represented as $a \times I \times PF$ in equation. (2). In contrast, other studies [47,53] measure the installed PV capacity, represented as $a_{i,j,l,k} \times AF_l \times DF_k$ 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 [46,47,49,53], energy losses associated with solar-to-electric power conversion and shading effects are divided into three components, represented as $PR \times \eta \times (1 - F_s)$ in equation (2). In contrast, other studies [54,55] apply a definition-based parameter, the capacity factor, represented as CF_j 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 Materials.

2.2.1 Area factor: total area to PV system area

Fig. 2 (c) illustrates the graphical concept of the area factor (AF_l). 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 [45,56,57]. 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 factors differ based on the land-use types. 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 [58]. Meanwhile, for water-surface PV systems, the area factor varies widely in prior research, ranging from 1% to 100% % [59–64]. Based on these findings, this study adopts an assumed area factor of 25% for water-surface PV installations.

2.2.2 Density factor: PV system area to PV capacity

Fig. 2 (d) illustrates the graphical concept of the density factor (DF_k), 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 m^2/kW for single-family buildings, and 4.7 m^2/kW for both multi-family and apartment complexes [65]. For ground-mounted PV systems, density factors of 9.57 m^2/kW and 13.16 m^2/kW were reported in previous studies [66,67]. To improve land-use efficiency, emerging PV technologies such as PV trees [66–68] and agricultural PV [69–71]. 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. To achieve 1kW of capacity, roof-top PV systems require an average of 7.23m^2, whereas ground-mounted PV systems require 11.50m^2 on average. For water-surface PV systems, where case data is unavailable, a density factor of 10 m^2/kW is assumed based on previous studies [62].

2.2.3 Capacity factor: PV capacity to PV generation

Fig. 2 (e) illustrates the graphical concept of the capacity factor (CF_k), 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 [72]. Over the past six years, the national average capacity factor for 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%.

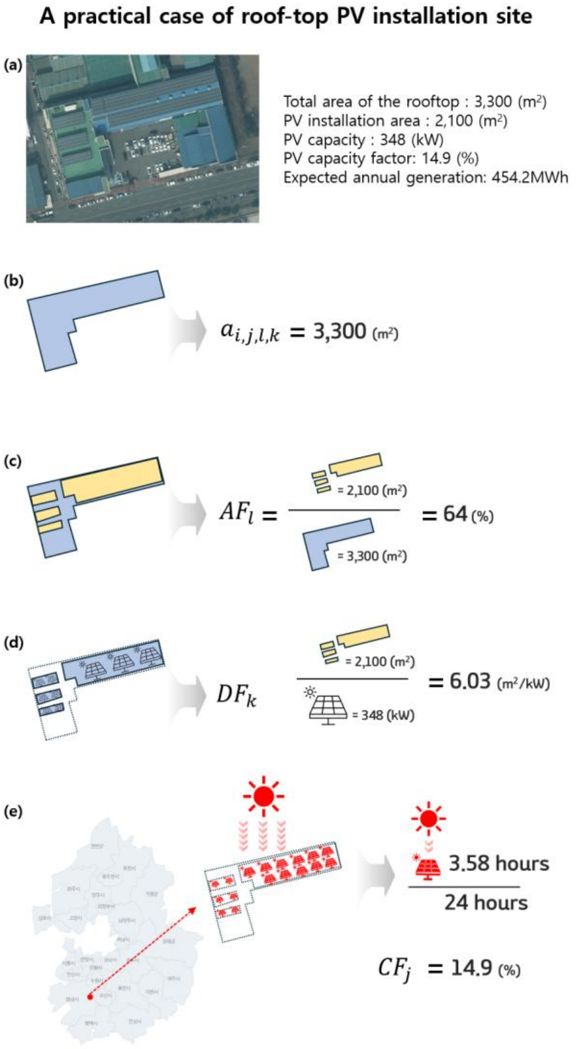

Fig. 2. Graphical concept of generation calculation method

2.3 Levelized costs of energy

The LCOE is a widely recognized metric for evaluating the economic performance of power generation technologies. It provides a standardized measure of the cost per generation over the lifetime of a generation system. The Korea Energy Economics Institute (KEEI) conducts comprehensive studies on LCOE, analyzing it by energy source, technology type, and region from a financial perspective [73]. The LCOE formula is expressed as following equation (4) (see Supplementary Materials for details). The calculation of LCOE considers various costs incurred over the lifetime(t) of a PV system. These costs include the capital expenditure ($Capex$), which represents the initial investment required for installing the PV system. Additionally, operating expenditure ($Opex_t$) accounts for the annual costs of operating and maintaining the system. Another important cost is the interest expense (Int_t), reflecting the financial costs associated with borrowing capital for the project. Similarly, the land lease expense (LE_t) includes the annual costs of leasing land for PV operations. Finally, the calculation incorporates the corporate tax (Tax_t), representing the taxes applied to the revenues obtained from the PV system. The denominator of the LCOE formula includes the electricity generation (Q) of the PV system, adjusted for its degradation rate (d) over time. Except for the initial capital expenditure ($Capex$), all other costs are annual expenditures or benefits. These are levelized over the system's lifetime (t) using a financial discount rate (r)[1].

$$LCOE = \frac{Capex + \sum_{t=1}^{T} \frac{1}{(1+r)^t} (Opex_t + Int_t + LE_t + Tax_t)}{\sum_{t=1}^{T} \frac{1}{(1+r)^t} Q(1-d)^t} \quad (4)$$

The variation in solar irradiation and land prices across South Korea's regions was incorporated into the LCOE analysis. The LCOE data are classified by 250 administrative local areas across the nation and PV types (ground-mounted and roof-top PV). For Gyeonggi Province, the region is divided into 42 local areas (reflecting 31 counties, with 6 of them further analyzed at the town level) in the LCOE data. LCOE values were calculated separately for ground-mounted and roof-top PV in each of these areas and were utilized for this study.

In 2020, the LCOE for ground-mounted PV in South Korea ranged from 123.4 Won/kWh (for 20 MW installations) to 152.0 Won/kWh (for 100 kW installations). This variation by installation size reflects economies of scale, where larger installations achieve lower costs per unit of generation. However, LCOE differences across regions were even greater, driven by geographical factors (solar irradiation), regulatory factors (restrictions on developable land), and economic factors (land prices). In Gyeonggi Province, the lowest LCOE for ground-mounted PV was recorded in Yeoncheon County at 146 Won/kWh, while the lowest LCOE for roof-top PV was 129 Won/kWh. Conversely, the highest LCOE was observed in Dongan-gu in Anyang-si, with 1,140 Won/kWh for ground-mounted PV and 1,121 Won/kWh for roof-top PV.

2.4 Setback regulation scenario

In Gyeonggi Province, 12 out of the 31 cities have implemented setback regulations (see Supplementary Materials for details). These regulations define minimum distances between PV installations and specific locations, including residential housing, roads, rivers, tourist attractions, natural parks, educational institutions, medical facilities, cultural heritage sites, historic sites, public sports facilities, and natural habitation areas. Residential housing (11 cities), roads (10 cities), and cultural heritage sites (6 cities) are the most frequently regulated by setback requirements. The setback distance from residential housing ranges between 100 meters and 500 meters depending on the city. For roads and cultural heritage sites, the setback distance is regulated between 100 meters and 300 meters. Fig. 3(a) shows the location of Gyeonggi Province within South Korea, and Fig. 3(b) illustrates the areas affected by these setback regulations within Gyeonggi Province. To analyze the impact of setback regulations, this study considers two scenarios as shown in Table. 1.

Table. 1. Scenario description

Scenario	Description
Current Setback	PV generation potential under the existing setback regulation. This considers minimum required distances from locations such as residential area roads, cultural heritage and others
No Setback	PV generation potential without applying any setback regulation, allowing installations without distance constraints.

[1] 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[81].

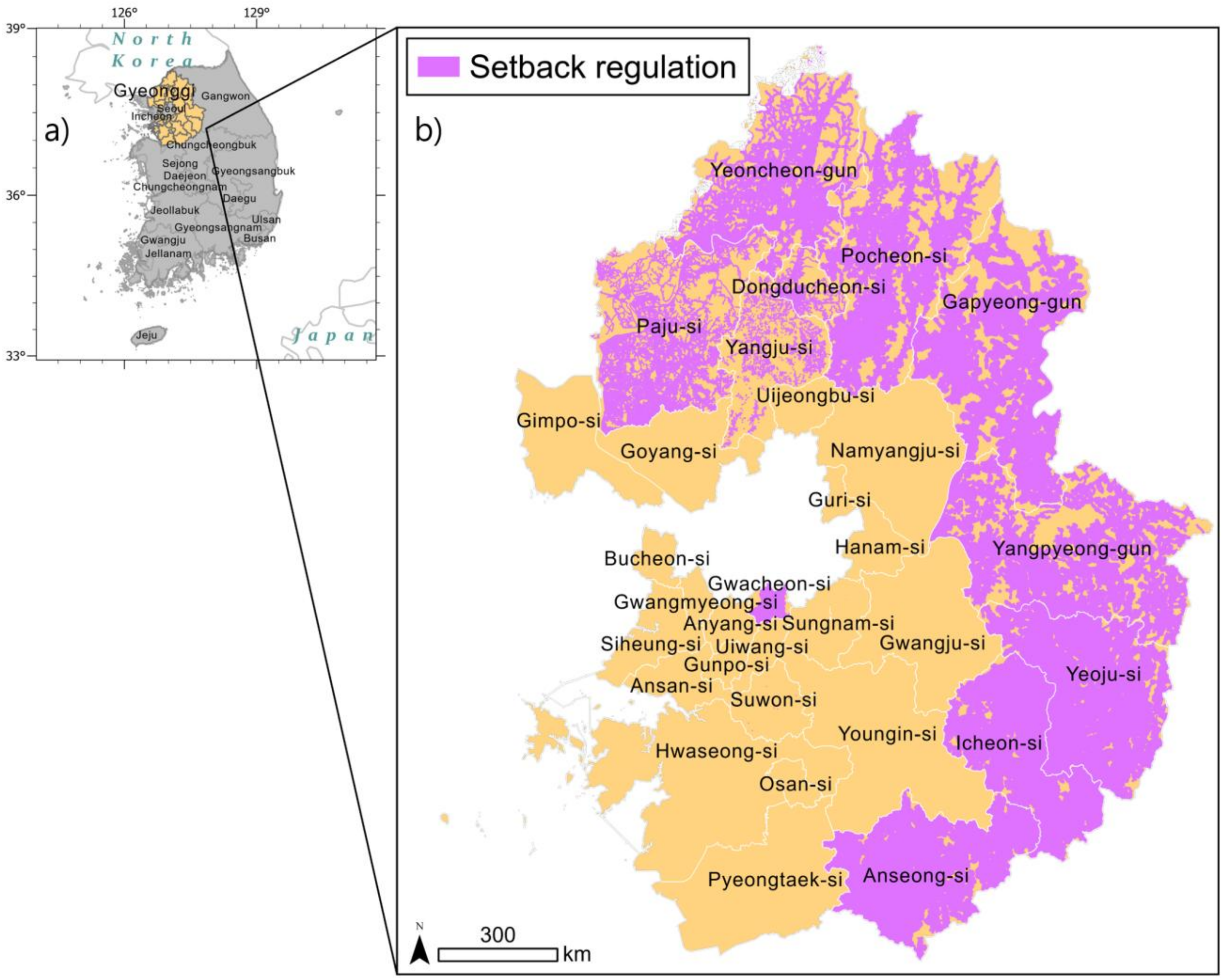

Fig. 3. Setback regulation area: a) Location of Gyeonggi province in South Korea, b) status of setback regulations

Table. 2. Assumed parameters for PV potential and LCOE analysis

Land-use type	PV type	Assumed parameters for calculating potential			LCOE
		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	Water-surface PV	25	10		

3. Results and discussion

3.1 Geographic & technical potential of PV

Fig. 4(a) shows the PV-eligible sites under the No Setback scenario, while Fig. 4(b) provides a magnified view of selected areas, showcasing PV-eligible sites across all land-use types. Table. 3 summarizes the geographic & technical potential analysis in Gyeonggi Province, focusing on available PV-installation area, capacity, and annual generation under the Current Setback and No Setback scenarios. First, the total area available for PV installation in Gyeonggi Province under the Current Setback scenario is 682.45 km^2, accounting for 6.7% of the province's total area (10,171 km^2). Under the No Setback scenario, the available area increases significantly by 78.42%, reaching 1,217.60 km², or 12% of the province's total area. Second, the PV capacity potential also shows a notable difference between the two scenarios. In the Current Setback scenario, the PV capacity is estimated at 8.97 GW. By comparison, the No Setback scenario results in a 38.44% increase, with a total capacity of 12.41 GW. When compared to the 2022 PV capacity installed in Gyeonggi Province, which was 1.8 GW, the capacities in the Current Setback and No Setback scenarios represent 4.98 times and 6.89 times the existing capacity, respectively [6]. Furthermore, in terms of meeting Gyeonggi Province's PV deployment target of 9 GW, the Current Setback scenario falls short by 0.03 GW, whereas the No Setback scenario exceeds the target. Third, annual generation potential varies significantly between the two scenarios. In the Current Setback scenario, the annual PV generation potential is 10.87 TWh, which increases by 37.91% to 15.00 TWh under the No Setback scenario. These figures represent 7.8% and 10.7% of Gyeonggi Province's total electricity consumption in 2022 (140.6 TWh), respectively [74]. Under South Korea's carbon neutrality scenario, Gyeonggi province's contribution to the required PV generation (449TWh) is estimated at 2.4% and 3.3% under the Current Setback and No Setback scenarios, respectively.

To further understand these results, the analysis explores two key efficiency perspectives: i) land efficiency and ii) capacity efficiency. First, from the perspective of land efficiency, which examines how densely PV systems are installed relative to the available area, the Current Setback scenario achieves a value of 76.08 km² per GW. Under the No Setback scenario, this value increases to 98.11 km² per GW, reflecting a 28.96% reduction in efficiency. This decline in efficiency occurs because the No Setback scenario includes more land-use types, such as farmland and mountainous areas, which have lower area factors and higher density factors compared to urban land-use types. In Table. 3, the available area for farmland increases by 96.52%, and for mountainous areas by 87.06%, under the No Setback scenario. These increases are far greater than the 15.41% increase observed for residential areas. Additionally, a comparison of roof-top PV and ground-mounted PV systems under the Current Setback scenario highlights significant differences in land and generation efficiency. The total area for roof-top PV systems, which include residential, industrial, logistics, and public building installations, is 67.99 km². In contrast, the area for ground-mounted PV systems, such as farmland, mountainous areas, roadside land, and parking lots, is significantly larger at 565.46 km². Despite the smaller area, roof-top PV systems generate 6.18 TWh annually, nearly 1.92 times the 3.21 TWh generated by ground-mounted PV systems. This difference arises because roof-top PV systems are installed with higher area factors and lower density factors, enabling more efficient land use. Second, from the perspective of capacity efficiency (i.e. capacity factor), the Current Setback scenario achieves 1.212 TWh per GW. This figure decreases slightly to 1.209 TWh per GW in the No Setback scenario, representing a 0.25% reduction. While this decrease is not substantial, it indicates that the No Setback scenario includes regions with lower capacity factors, which contribute less efficiently to electricity generation.

Overall, while the No Setback scenario increases the total area and capacity available for PV installation, it results in reduced efficiency in land and capacity utilization. These findings highlight the importance of balancing quantitative expansion with qualitative efficiency in PV deployment strategies.

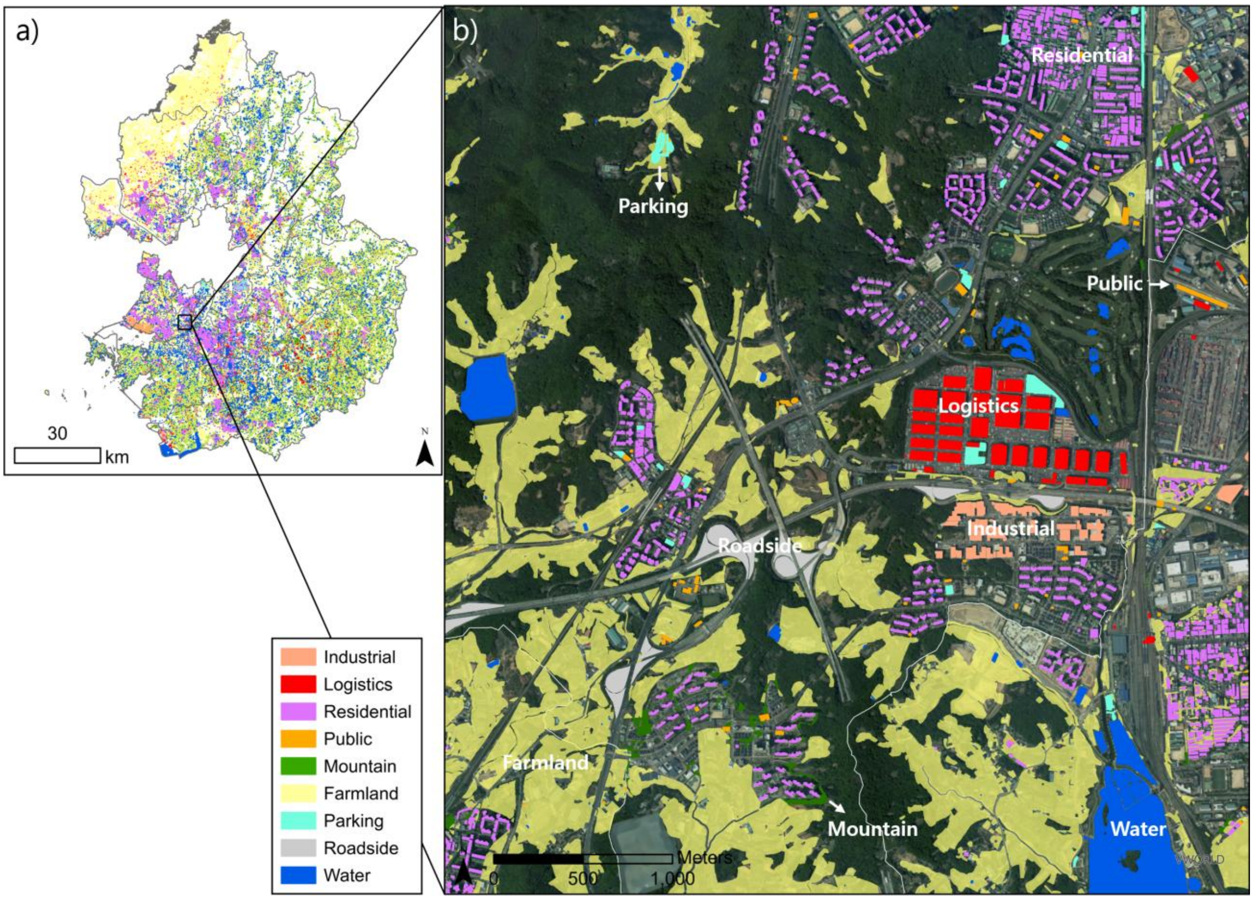

Fig. 4. Spatial distribution of PV-eligible installation sites under No Setback scenario: a) Overall distribution and b) magnified view of selected areas

Table. 3. Impact of setback scenarios on area, capacity, and generation by land-use type.

Land-use type	Area (km^2, %)			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

* Inc (%) refers to the percentage increase from the Current Setback scenario to the No Setback scenario.
** The numbers (%) in parentheses indicate the proportion of the total value.

Fig. 5 shows the potential increase in PV generation for land-use types when setback regulations are removed. Detailed numerical values are available in Table 3. In Gyeonggi Province, residential areas account for the highest potential generation in both scenarios due to the region's high population density. Although Gyeonggi Province represents only 10.2% of South Korea's total land area, it accommodates 27.4% of the nation's population. This concentration of people results in a large number of residential buildings, which translates to significant PV potential. Under the Current Setback scenario, residential areas have a PV generation potential of 3.49 TWh, which increases by 15.19% to 4.02 TWh in the No Setback scenario. These values correspond to 16.52% and 19.03% of Gyeonggi Province's total residential electricity consumption in 2021, which was 21.13 TWh. Industrial and logistics are critical for achieving corporate RE100 targets, particularly as companies often prefer off-grid PPAs for self-consumption. This makes roof-top PV installations in these areas highly advantageous. In industrial, the potential generation under the Current Setback scenario is 2.00 TWh, increasing by 16.52% to 2.33 TWh in the No Setback scenario. Logistics show an even more significant increase, with potential generation rising from 0.29 TWh to 0.49 TWh, a 72.70% increase. Together, the industrial and logistics sectors account for 3.09% of Gyeonggi Province's total industrial electricity consumption in 2022 [74] under the Current Setback scenario and 3.81% under the No Setback scenario, which is equivalent to 74.07 TWh. Farmland and mountainous areas exhibit the largest increases in potential generation when setback regulations are removed. In farmland, potential generation rises from 1.54 TWh under the Current Setback scenario to 2.99 TWh under the No Setback scenario, an increase of 93.67%. Similarly, mountainous areas see potential generation increase from 1.44 TWh to 2.65 TWh, representing an 84.81% increase. However, deploying PV systems in these areas requires addressing concerns about horticultural impacts and ecosystem preservation. For farmland, promoting AgroPV systems, which allow both crop cultivation and PV generation, is essential to maximize benefits. Similarly, for mountainous areas, it is critical to balance greenhouse gas reductions with the need for ecosystem preservation to avoid green-on-green conflicts [75] . While PV has clear benefits for reducing greenhouse gas emissions, its installation can negatively affect the environment by reducing carbon absorption and disturbing natural habitats [76,77]. The potential generation on water surfaces also increases when setback regulations are removed, but the increase is comparatively modest. Under the Current Setback scenario, the potential generation from water surfaces is 1.49 TWh, which rises by 14.86% to 1.71 TWh under the No Setback scenario. This smaller increase reflects the limited impact of setback regulations on reservoirs, lakes, and dams, which are typically less affected by urban setback requirements. However, as with farmland and mountainous areas, deploying PV systems on water surfaces requires addressing environmental concerns. Water-surface PV systems[2], can lower water temperatures, reduce dissolved oxygen levels, and negatively impact plankton diversity and bird populations [78]. Public buildings, owned and operated by the government, represent a land-use type where PV deployment can be actively pursued through government initiatives. In the Current Setback scenario, the potential generation from public buildings is 0.40 TWh, increasing by 28.20% to 0.51 TWh in the No Setback scenario. These values correspond to 4.00% and 5.10% of the electricity consumption in Gyeonggi Province's public sector in 2022, which was 10.01 TWh. Given their high acceptance for PV deployment, public buildings offer a promising starting point for government-led PV initiatives. Roadside land also represents a promising opportunity for PV deployment. This land type is often unused and publicly owned, making it well-suited for PV installations. Under the Current Setback scenario, roadside land has a potential generation of 0.20 TWh, increasing by 27.07% to 0.26 TWh in the No Setback scenario. Similar to public buildings, roadside land benefits from high acceptance for PV deployment. Among all land-use types, parking lots have the lowest potential

[2] Water-surface photovoltaic systems are categorized into floating photovoltaic systems, where PV panels are installed on floating materials atop the water surface, and pile-mounted photovoltaic systems, where PV panels are fixed onto piles rather than floating.

generation. In the Current Setback scenario, parking lots generate 0.028 TWh, which increases by 21.45% to 0.034 TWh in the No Setback scenario. Despite the lower generation potential, parking lots offer a unique advantage as a dual-use land type, where PV systems can be installed without disrupting the land's primary purpose. This characteristic is shared with farmland, where PV systems can coexist with agricultural activities. In conclusion, the removal of setback regulations significantly increases the potential for PV generation across most land-use types, particularly in farmland and mountainous areas. However, this expansion requires careful consideration of land-use-specific challenges, such as environmental impacts, dual land use, and system efficiency.

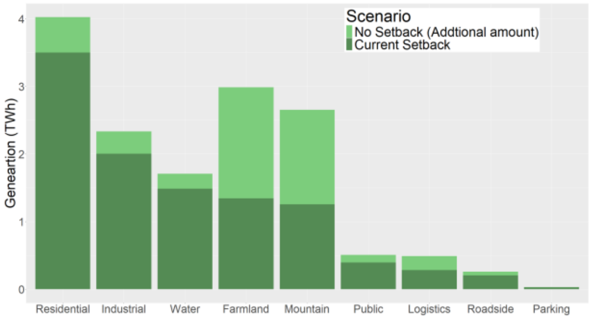

Fig. 5. Impact of setback regulation on potential by land-use type.

3.2 Geospatial supply curve and deployment strategies

The geospatial supply curve for PV generatino is derived by applying region- and type-specific LCOE values to individual PV-eligible plots. Fig. 6 illustrates the supply curves under both the Current Setback and No Setback scenarios. In the Current Setback scenario, the curve is represented by connecting the upper segments of the bar charts between points *f* and *m*. In the No Setback scenario, the curve is formed by connecting the segments between points *f* and *n*. Using these supply curves, three deployment strategies are proposed: price-based, quantity-based, and full deployment (Table. 4)

The first strategy, the price-based strategy, prioritizes the deployment of PV systems on sites with LCOE values lower than the System Marginal Price (SMP). These sites are represented by the bars below the horizontal line *g* in Fig. 6, which corresponds to the SMP for 2023. The generation under the price-based strategy represents economic potential. The second strategy, the quantity-based strategy, focuses on achieving Gyeonggi Province's PV deployment target of 9 GW. This involves the bars to the left of the *cl* line, representing the expected generation corresponding to the capacity target[3]. The third strategy, the full deployment strategy, entails deploying PV systems on all identified eligible sites. In the Current Setback scenario, this includes the bars to the left of the *dm* line, while in the No Setback scenario, it extends to the bars to the left of the *en* line.

The three strategies are analyzed in terms of five dimensions: generation, avoided emissions, generation costs, and the average costs of generation and avoided emissions.

In terms of generation, the price-based strategy produces the smallest generation potential among the three strategies. Under the Current Setback scenario, it yields 1.55 TWh of generation, as indicated by line *oa*, but increases by 161% to 4.04 TWh (line *ob*) in the No Setback scenario. However, neither scenario achieves the 9 GW target represented by line *oc*. In contrast, the quantity-based strategy achieves a fixed generation level of 10.72 TWh (line *oc*) in both scenarios since the strategy is designed to meet the quantity target. The full deployment strategy results in a generation potential of 10.87 TWh under the Current Setback scenario (line *od*), which increases by 37.91% to 15.00 TWh (line *oe*) in the No Setback scenario. Comparing the strategies, the full deployment strategy shows a larger absolute increase in generation (4.13 TWh) when setback regulations are removed compared to the price-based strategy (2.49 TWh). However, the relative increase is higher for the price-based strategy, at 160.65% versus 37.91% for the full deployment strategy. Examining the economic viability of generation, the share of economically viable potential increases from 14.26% (1.55 TWh/10.87 TWh) in the Current Setback scenario to 26.93% (4.04 TWh/15.00 TWh) in the No Setback scenario.

Avoided emissions are directly proportional to the PV generation potential, as they represent the greenhouse gas emissions avoided by replacing fossil fuel-based electricity generation with PV. Avoided emissions are calculated by multiplying the generation potential by the electricity emission factor of 0.4434 tCO_2/MWh [79]. For the price-based strategy, avoided emissions are 0.69 $MtCO_2$ under the Current Setback scenario, increasing by 1.10 $MtCO_2$ to 1.79 $MtCO_2$ in the No Setback scenario. In the quantity-based strategy, avoided emissions remain constant at 4.76 $MtCO_2$ due to the fixed generation level. The full deployment strategy results in avoided emissions of 4.82 $MtCO_2$ under the Current Setback scenario, which increases by 1.83 $MtCO_2$ to 6.65 $MtCO_2$ in the No Setback scenario. These figures correspond to 5.49% and 7.58% of Gyeonggi Province's total greenhouse gas emissions in 2021, which were 87.74 $MtCO_2$.

Generation costs, representing the annual costs of PV electricity generation, are calculated as the generation potential and LCOE. In the quantity-based strategy, generation costs are 2,808.7 million USD under the Current Setback scenario. This cost decreases to 1,609.4 million USD under the No Setback scenario, representing a 42.7% reduction in costs while maintaining the same generation level of 10.72 TWh. The relative costs of each strategy can be visually identified as the area under bars in Fig. 6 and are summarized in Table. 4.

To account for both benefits and costs, the average costs of generation and avoided emissions are evaluated. Among all strategies, the price-based strategy under the No Setback scenario achieves the lowest average cost of generation at 121.7 USD/MWh. Under the Current Setback scenario, the price-based strategy's average generation cost is 124.3 USD/MWh, which decreases by 2.09% to 121.7 USD/MWh in the No Setback scenario. In the quantity-based strategy, average generation costs decrease significantly from 261.9 USD/MWh under the Current Setback scenario to 150.1 USD/MWh under the No Setback scenario, representing a 42.69% reduction. The full deployment strategy shows a smaller reduction, with average generation costs decreasing from 270.4 USD/MWh under the Current Setback scenario to 230.7 USD/MWh under the No Setback scenario, a reduction of 14.68%. The impact of removing setback regulations on cost reductions is most pronounced in the quantity-based strategy (42.69%), followed by the full deployment strategy (14.68%) and the price-based strategy (2.09%).

Overall, the removal of setback regulations results in significant increases in generation potential and avoided emissions across all strategies. However, the relative impact on costs and efficiency varies, with the quantity-based strategy showing the largest cost reductions and the price-based strategy exhibiting the most substantial relative increase in generation potential.

[3] Assuming an average capacity factor of 13.6% for Gyeonggi Province, the annual generation expected from 9 GW is 10.72 TWh.

Table. 4. Comparative evaluation of PV deployment strategies: costs, emissions, and generation under setback scenarios.

Deployment strategy		Scenario	Generation (TWh) (A)	Avoided emissions ($MtCO_2$) (B)	Generation costs (Million USD) (C)	Average costs of generation (USD/MWh) (C/A)	Average costs of avoided emissions (USD/tCO_2) (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

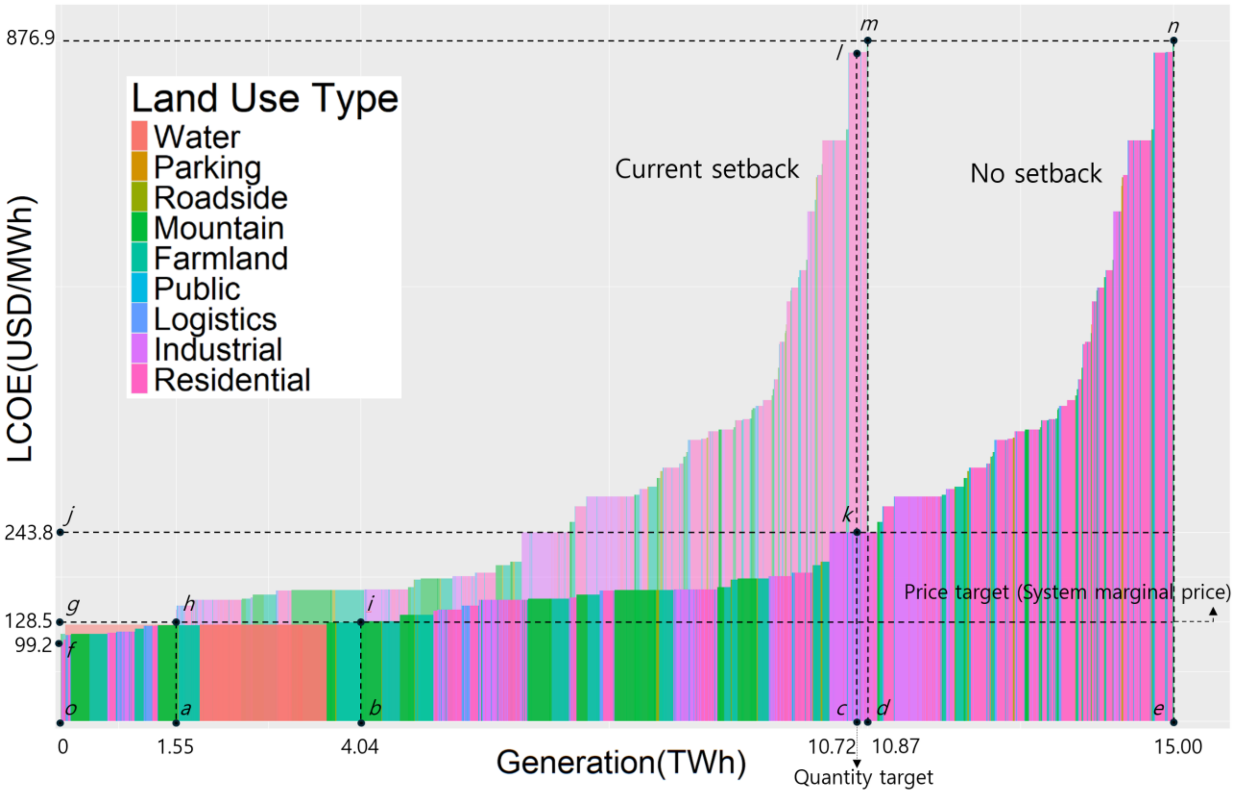

Fig. 6. Geospatial supply curve of PV generation: Current vs. No Setback scenarios.

4. Conclusions and policy implications

This study investigates PV potential in Gyeonggi Province, South Korea, the region with the highest population and electricity consumption among the country's 17 provinces. Using GIS-based spatial analysis, this study identified PV-eligible sites at the granularity of individual plots and categorized them by land-use type. Real-world PV installation data were employed to calculate key efficiency parameters, including the area factor, density factor, and capacity factor, for each land-use type. These parameters were then applied to estimate the potential capacity and generation for each plot. To further refine the analysis, site-specific LCOE data were integrated to construct a geospatial supply curve for PV generation. This supply curve served as the foundation for formulating three distinct deployment strategies: price-based, quantity-based, and full deployment. The benefits and costs associated with each strategy were rigorously evaluated.

The removal of setback regulations yielded substantial increases in PV deployment potential: installation area expanded by 78.42%, capacity increased by 38.44%, and generation potential rose by 37.91%. However, while these results indicate an increase in technical feasibility, this study highlights the importance of assessing efficiency metrics to understand the broader implications. When setback regulations were removed, the expansion of land-use types such as farmland and mountainous areas—characterized by lower area factors and higher density factors—resulted in reduced land-use efficiency, with fewer PV systems installed per unit area. Additionally, the specific environmental vulnerabilities of these land-use types raise concerns about unintended ecological consequences. This finding underscores the need for differentiated regulatory frameworks or incentive policies tailored to the characteristics of each land-use type, rather than applying uniform regulations. A marginal decline in capacity efficiency with the removal of setback regulations, combined with the decrease in land-use efficiency, suggests that while the removal of setback regulations enhances the potential, it may dilute overall deployment efficiency. To mitigate this issue, strategies to increase the adoption of roof-top PV systems, which are inherently more efficient, should be prioritized.

Across both scenarios, the residential sector consistently accounted for the largest share of PV generation potential. This finding indicates that policies aimed at supporting roof-top PV installations on residential buildings could be instrumental in accelerating deployment during the early stages of a PV rollout. Notably, the government has announced plans to formally introduce Renewable Energy Certificates (RECs) for self-consumption PV starting next year, which could significantly boost new PV installations in the residential sector. The industrial and logistics sectors also hold considerable strategic value, particularly for achieving corporate RE100 targets. Given ongoing discussions on implementing a regional differentiated electricity pricing system based on energy self-sufficiency rates, industries in Gyeonggi Province—which has a low energy self-sufficiency rate—face expected economic pressures from rising electricity costs. Deploying PV systems in these sectors not only facilitates RE100 commitments but also provides a cost-effective solution for mitigating electricity price risks. In farmland, mountainous areas, and water bodies, this study emphasizes the need for strategies that minimize environmental impacts. For farmland, promoting AgroPV systems that enable simultaneous agricultural production and PV generation can address both economic and ecological concerns. In mountainous areas, the focus should be on balancing greenhouse gas reduction with ecosystem preservation to mitigate potential "green-on-green" conflicts. Water surfaces offer opportunities for PV deployment; however, the environmental implications of water-surface PV systems—such as changes in water temperature, dissolved oxygen levels, and biodiversity—must be carefully managed. Conversely, public and roadside land, being government-owned and managed, offer straightforward opportunities for PV deployment, provided there is sufficient policy support.

The geospatial supply curve formed the basis for evaluating three deployment strategies: price-based, quantity-based, and full deployment. The price-based strategy, which prioritizes economically viable sites, falls short of achieving Gyeonggi Province's PV deployment targets, demonstrating that economic feasibility alone is insufficient to meet quantitative goals. In contrast, the full deployment strategy, which involves deploying PV systems on all identified eligible sites, achieves the province's PV target by leveraging the maximum geographic & technical potential. These findings highlight the need for government incentives to make less viable sites contribute to deployment goals and bridge the gap between feasibility and targets.

Of the three strategies, the price-based strategy exhibited the highest relative increase rate in generation potential following the removal of setback regulations. This result suggests that in the early stages of PV development, a price-based strategy could efficiently expand deployment. Conversely, it experienced the largest potential generation loss under setback regulations, highlighting that such regulations impose not only spatial constraints but also significant economic barriers.

The proportion of economic potential generation relative to geographic & technical potential increased from 14.26% under the Current Setback scenario to 26.93% under the No Setback scenario. This shift indicates that removing setback regulations enhances the economic feasibility of PV projects, improving profitability and lowering average generation costs. Across all strategies, the price-based strategy demonstrated the lowest absolute generation costs, followed by the quantity-based strategy and the full deployment strategy, regardless of whether setback regulations were in place. These findings align with the observation that the removal of setback regulations reduced the average cost per unit of generation across all strategies. Notably, the quantity-based strategy exhibited the highest cost reduction rate, highlighting its potential as a scalable and cost-efficient approach for PV deployment. While the full deployment strategy had the highest costs, it remains the most effective strategy for maximizing PV deployment, as it prioritizes installing systems on all identified plots, including those with lower economic returns.

The findings suggest that the removal of setback regulations improves cost efficiency across all strategies. However, strategy selection must balance cost-efficiency with deployment goals. In the short term, a price-based strategy is effective for accelerating deployment, while a quantity-based strategy offers greater scalability in the medium term. In the long term, achieving ambitious targets such as national carbon neutrality may necessitate adopting a full deployment strategy. For instance, under the full deployment strategy, removing setback regulations could result in 6.65 $MtCO_2$ of avoided emissions, equivalent to 1% of South Korea's total emissions in 2021 and 7.6% of Gyeonggi Province's emissions.

While this study provides a comprehensive analysis of the impacts of setback regulations, it acknowledges several limitations. First, this study contrasts two extreme regulatory conditions — full application versus complete removal of setback regulations. Although this approach provides clear policy contrasts, it does not capture potential incremental reforms that could involve partial relaxation of setback distances. Future research could explore a wider range of intermediate scenarios to better reflect practical policy pathways. Second, this study does not conduct sensitivity analyses on input parameters such as area, density, and capacity factors. Variations in these parameters could affect the estimated deployment potential and cost-efficiency. Systematic sensitivity testing in future work would enhance the robustness and reliability of policy recommendations. Third, limitations exist in the LCOE data utilized. Previous studies categorize LCOE into four key components: Plant Performance, Investment-Related Costs, Operation-Related Costs, and Risk & Uncertainty [80]. However, the LCOE data in this study does not fully account for two aspects. First, the costs associated with intermittency are not included. Due to the intermittent nature of PV generation, additional expenses are incurred for grid integration, reserve capacity, and ancillary services such as frequency and voltage regulation. These integration costs are essential for maintaining system stability and efficiency as PV systems are integrated into the existing grid. Second, the analysis excluded the effects of government subsidies and policy incentives. In reality, PV projects often benefit from various forms of financial support, including subsidies, tax credits, and other incentives, which significantly influence economic viability. While this exclusion means the analysis does not fully capture the financial realities experienced by PV system operators, it aligns with this study's intent to focus on societal-level costs. Subsidies, though excluded here, represent government expenditures and thus contribute to the overall societal cost of PV deployment.

CRediT authorship contribution statement

Seungho Jeon: Writing – original draft, Writing – review and editing, Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization. **Han Soo Kim:** Project administration, Funding acquisition

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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