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Assessment of light environmental impacts from offshore wind farms in South Korea☆

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ABSTRACT

Offshore wind farms are expanding rapidly as a clean energy solution but raise concerns about light-related environmental impacts, such as shadow flicker and light pollution, affecting ecosystems and human communities. This study assesses the light environmental impacts of offshore wind farms in South Korea, specifically evaluating daytime shadow flicker and nighttime light pollution, and proposes mitigation strategies tailored to diverse landscape contexts. Using advanced geospatial tools, including QGIS and WindPRO, light-related disturbances were analyzed across three representative sites: Aphae (rural), Jangbogo (island), and Dadaepo (urban). Shadow flicker exposure was quantified based on turbine specifications, solar dynamics, and observer locations, while light pollution from aviation obstruction lights was assessed through spatial luminance analysis. The Aphae site exhibited the highest shadow flicker exposure, with up to 154 days annually and 79 h per year in some regions, while Dadaepo's urban zone displayed moderate impacts, particularly in tourist areas like Molundae Observatory. Jangbogo experienced negligible effects due to natural buffering and greater separation distances. Light pollution intensity correlated with proximity and turbine visibility, with 8–13 turbines visible in highly impacted zones. Tailored mitigation strategies, such as optimized turbine placement, green buffers, zoning regulations, and habitat preservation, are essential to minimizing adverse impacts. This research underscores the need for location-sensitive planning to achieve sustainable offshore wind energy development while safeguarding ecological and human well-being.

1. Introduction

As numerous nations transition to the new climate regime, the implementation of renewable energy technologies for carbon neutrality has accelerated dramatically (Elavarasan et al., 2021; Li et al., 2024a, 2024b; Nielsen, 2022; Xinyu et al., 2024). Among renewable energy technologies, offshore wind farms have gained significant attention as a clean energy source due to its advantages over the other technologies (Popat, 2021). The first advantage is that they can guarantee higher and steadier wind speed compared to onshore location, allowing for greater energy capture and generation (Josimović et al., 2021; Li et al., 2024a; Barthelmie and Jensen, 2010). Second, offshore wind farms can accommodate larger and more powerful wind turbines, further increasing energy generation potential (Castro-Santos et al., 2018; Josimović et al., 2021). Driven by these distinctive characteristics, the offshore wind energy sector has experienced rapid growth, currently representing a substantial 40–50 % of global renewable energy installation portfolios (Colmenar-Santos et al., 2016; Kim et al., 2018; Lee, 2022). Particularly, South Korea, with its geographical situation of being surrounded by the sea on three sides, is one of the leading nations actively advancing offshore wind energy development (Choi et al., 2024; Kee and Zhao, 2024). By setting a 2030 target of 6 GW and an estimated capacity of approximately 115.38 MW per million people, the country demonstrates a strong commitment to expanding renewable energy in alignment with its population scale (Park et al., 2021).

Currently, the rapid expansion of offshore wind farms in South Korea has led to indiscriminate installations, posing substantial challenges. Key issues include disruptions to marine ecosystems, such as alterations

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in fish habitats and migratory patterns, structural instability resulting from seabed erosion, and visual impacts, including modifications to the light environment through shadow flicker and light pollution (Li et al., 2024a; Gee, 2010; Kempton et al., 2005). Among these challenges, the modifications to the light environment are of particular interest due to their far-reaching implications. Shadow flicker and light pollution disrupt the natural behaviors and life cycles of marine and terrestrial wildlife while also affecting human communities through health concerns and practical disturbances (Bashiri, 2014; Knopper et al., 2014; Harding et al., 2008; Rand and Hoen, 2017). Light pollution from artificial lighting at night can also have significant impacts on wildlife. It can disrupt the circadian rhythms, seasonal behaviors, and migration patterns of many species (Falchi et al., 2016; Chen and Dong, 2023). Light pollution has been linked to declines in biodiversity and ecosystem stability (Leng et al., 2019). For human communities, shadow flicker and light pollution can also cause practical disturbances and health concerns. Shadow flicker from wind turbines has been found to be a significant annoyance to nearby residents, potentially leading to self-reported health effects like sleep disturbance (Adaramola, 2015; Haac et al., 2022). Light pollution has been associated with various human health issues, including depression, insomnia, and disruption of the circadian clock (Falchi et al., 2019; Infantino et al., 2021; Yu, 2023). In other words, to investigate the impacts of offshore wind farms on the light environment, it is essential to analyze shadow flicker and light pollution simultaneously. The extent and intensity of these impacts are highly dependent on geographical, social, ecological conditions of offshore wind farm locations.

To deal with socio-ecological issues caused by light environmental impacts, recent urban and landscape planners have tried to implement mitigation strategies including turbine placement, green infrastructure, zoning regulations, and habitat preservation. First, strategically placing and designing wind turbines can significantly reduce shadow flicker impacts on both nearby residences and wildlife habitats. Specific strategies include curtailing turbine operation during sensitive periods and optimizing turbine layout and orientation to minimize disturbances (Rogers, 2020). Second, incorporating green infrastructure, such as urban forests, green roofs, and water bodies, serves as an effective solution to mitigate light pollution. These nature-based approaches not only reduce artificial lighting's ecological impacts but also enhance urban sustainability (Hamling, 2024). Third, the development of zoning regulations and land use plans plays a critical role in limiting over-illumination. Effective measures include enforcing proper shielding and directionality of artificial lighting to reduce light pollution and its associated ecological disturbances (Gan et al., 2023; Samoylova, 2023). Fourth, preserving and expanding natural habitats and wildlife corridors is essential for minimizing disruptions to circadian rhythms and migration patterns of species affected by light pollution. These efforts contribute to biodiversity conservation and ecological balance (Chen and Dong, 2023; Leng et al., 2019).

To summarize related prior research, offshore wind farms are a critical solution for sustainable energy supply; however, the resulting changes in the light environment can negatively impact local ecosystems and community well-being. To address these issues, several research gaps need to be filled. First, it is essential to perform geospatial analyses of these impacts and develop effective mitigation strategies (Carpenter et al., 2016; Moon et al., 2024). Second, while existing studies predominantly address light pollution and shadow flicker separately, these phenomena often occur simultaneously in the real-world, being able to produce complex effects (Rogers, 2020). An integrated approach that examines both factors together is necessary to establish more practical and effective mitigation strategies. Third, the impacts of light environment changes and the corresponding mitigation measures vary based on the location and characteristics of offshore wind farms (Gavériaux et al., 2019; Adekanmbi et al., 2024). Nevertheless, research offering tailored solutions that account for these spatial and situational differences remains insufficient. This highlights the urgent need for studies that comprehensively analyze the light environment impacts of offshore wind farms and propose landscape planning strategies that are customized to their specific locations. In particular, geospatial analyses of light pollution and shadow flicker, combined with the development of location-sensitive mitigation strategies, are indispensable for advancing sustainable offshore wind energy development.

In this context, this study aimed to conduct a comprehensive geospatial analysis of light environmental impacts associated with offshore wind farms in South Korea, with a specific focus on quantifying and mapping daytime shadow flicker and nocturnal light pollution. Based on this analysis, the study seeks to propose landscape planning strategies to minimize these impacts.

2. Methodology and materials

2.1. Offshore wind farms in South Korea

South Korea, located between latitudes 33°N to 43°N and longitudes 124°E to 132°E, is bordered by the sea on its eastern, western, and southern coasts, offering an extensive coastline highly suitable for offshore wind development (Kim et al., 2016). The Yellow Sea, characterized by shallow waters less than 50 m deep, provides ideal conditions for offshore wind farm installations (Park and Kim, 2019). Furthermore, the southern waters adjacent to the mainland exhibit average wind speeds exceeding 6 m/s, making this region particularly advantageous for wind energy generation. As a result, the western and southern coasts of South Korea present optimal conditions for establishing renewable energy facilities, thereby supporting South Korea's renewable energy goals and its objective of achieving carbon neutrality (Yoon and Jung, 2021). The southwestern coast is uniquely distinguished by over 2000 islands, including the Shinan Dadohae Biosphere Reserve, designated by UNESCO in 2009, as well as coastal national parks, protected natural areas, fisheries, aquaculture operations, and major shipping routes (Kim et al., 2018). The ria coastline of this region, dotted with islands, encompasses diverse habitats such as sandy beaches, gravel shores, and mudflats, which not only sustain rich biodiversity but also provide significant socio-economic benefits through fisheries, tourism, and industrial activities (Cho, 2013).

The deployment of offshore wind farms in coastal areas of South Korea significantly alters the light environment, introducing challenges that impact both ecosystems and local communities. Light pollution from aviation obstruction lights and shadow flicker caused by rotating turbine blades are primary contributors to these changes, with potentially wide-ranging ecological and socio-economic effects. This study focuses on South Korea as a case study, owing to its increasing investment in offshore wind energy and the diverse coastal landscapes that present an ideal testing ground for evaluating these impacts. South Korea's strategic push for renewable energy, as part of its "Renewable Energy 3020 Implementation Plan," has resulted in numerous offshore wind farms under development, particularly in the southern and western seas. These regions were chosen for their favorable wind conditions, shallow waters, and geographical accessibility. Notably, the South Sea and the Yellow Sea host some of the country's most representative offshore wind farm projects, offering a rich diversity of coastal landscapes, including urban, rural, and island landscapes.

This study examines three representative offshore wind farms in South Korea, each selected to reflect distinct landscape typologies—rural, island, and urban—along the country's southern and southwestern coasts (Fig. 1). First, the Aphae offshore wind farm in Sinan-gun represents a rural landscape, characterized by agricultural and fishing activities interwoven with natural scenery, including tidal flats and marine national parks (Fig. 1A). Second, the Jangbogo offshore wind farm, located in Wando-gun, is situated within a typical island landscape, encompassing a ria coastline with rich marine biodiversity and numerous small islands (Fig. 1B). Finally, the Dadaepo offshore wind farm is positioned offshore of Dadaepo Beach in Busan, a densely

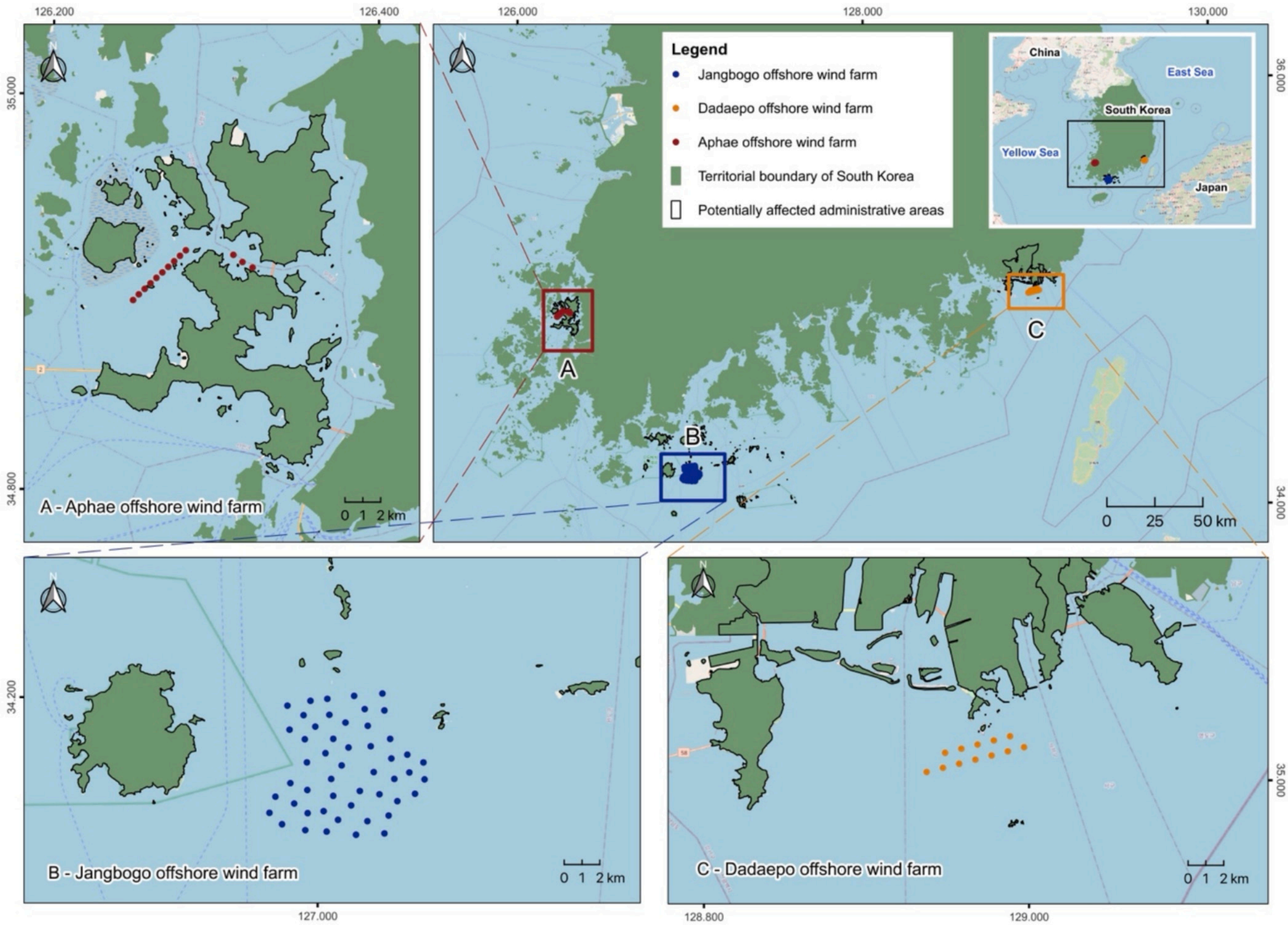


Fig. 1. Study sites: (A) Aphae offshore wind farm in the red box, (B) Jangbogo offshore wind farm in the blue box, and (C) Dadaepo offshore wind farm in the yellow box. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

populated urban area renowned for its tourism, commerce, and coastal recreational spaces (Fig. 1C). By categorizing the study sites into rural, island, and urban landscapes, this research enables a comparative analysis of the visual, ecological, and socio-economic impacts of offshore wind farms in diverse geographical and environmental contexts. This approach allows for a nuanced evaluation of light environment impacts and provides tailored mitigation strategies for each landscape type.

2.2. Research flowchart

The research flowchart outlines a systematic methodology for evaluating and mitigating the light environmental impacts of offshore wind farms (Fig. 2). The process begins by deriving the zone of potential light environment impact, which includes determining the viewshed and shadow impact area based on the distance from the wind farm. The next step involves assessing light environmental impacts through two key components: shadow flicker during the daytime, analyzed by configuring turbine specifications and sun positioning, and light pollution at nighttime, addressed by aligning turbine layouts and configuring aviation obstruction lights. Finally, mitigation strategies are proposed, emphasizing landscape planning solutions such as green infrastructure, optimized turbine placement, zoning regulations, and habitat preservation to reduce ecological and visual disturbances.

2.3. Data collection

To ensure a robust assessment of the light environmental impacts associated with offshore wind farms, a diverse range of datasets was systematically collected and categorized into geographical data, wind turbine data, environmental data, and population and land use data (Table 1). Each dataset was selected to address specific analytical needs, ensuring a comprehensive and integrated evaluation.

Digital Elevation Models (DEMs), sourced from the National Geographic Information Institute, provided terrain elevation data measured in meters. These models were essential for conducting visibility analyses and assessing the shadow impact of turbines in relation to topographical features. Coastline data from the same source supplied precise location information on coastal boundaries, enabling the contextual mapping of turbine installations relative to adjacent land and sea.

The geographical coordinates of individual wind turbines were acquired from construction companies, forming the spatial basis for mapping turbine locations. Technical specifications of the turbines, including model type, height, and rotor diameter, were sourced from the Wind Energy Database. These parameters, measured in meters, were pivotal for modeling both light pollution from aviation obstruction lights and the shadow flicker effects of turbine blades. Additional data on inter-turbine spacing, expressed in meters, and the total number of turbines installed at each site were provided by construction companies, allowing for an evaluation of turbine layout and cumulative impacts.

Seasonal sunrise and sunset times for the summer and winter

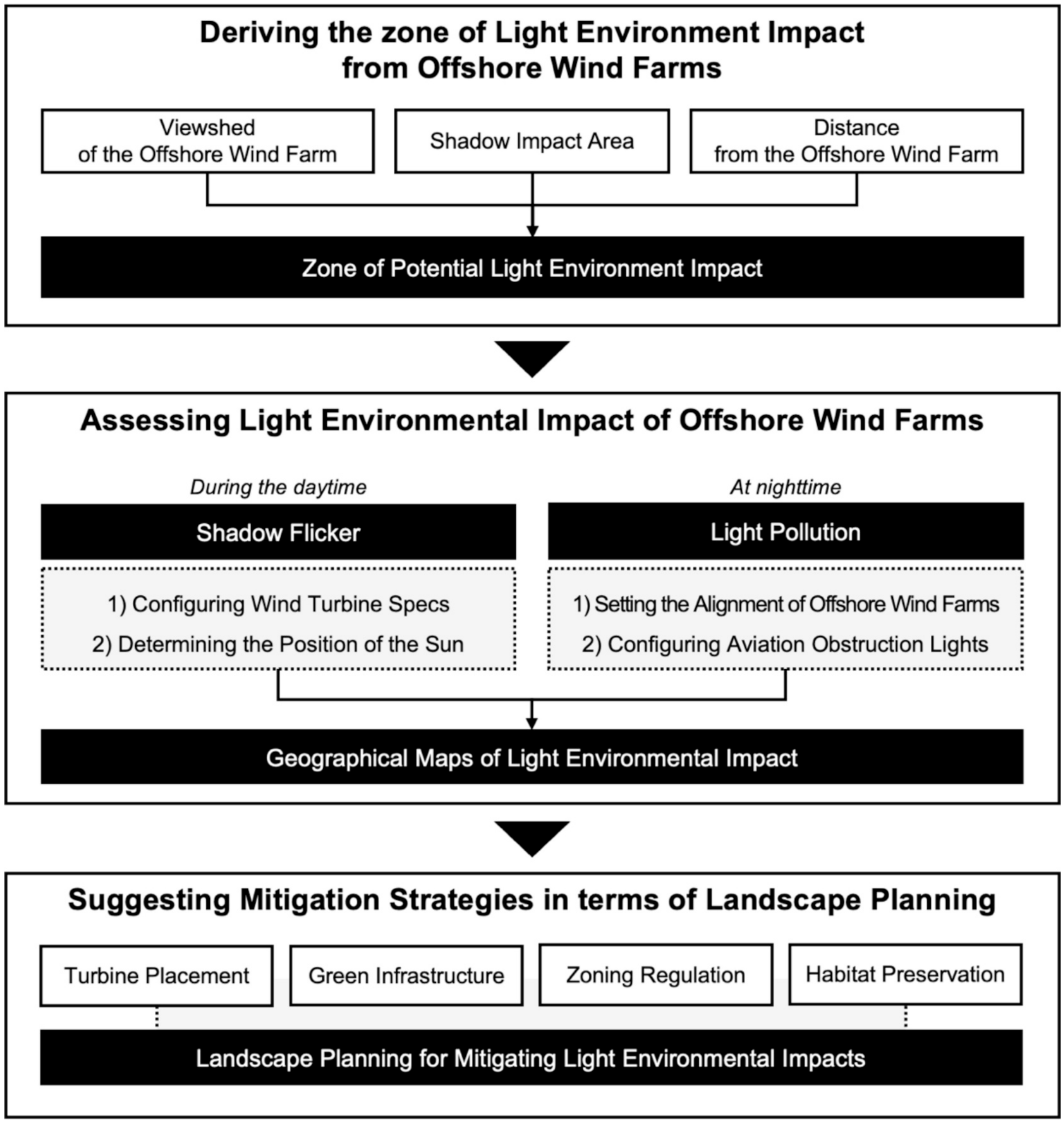


Fig. 2. Research flowchart.

solstices were obtained from the Korea Meteorological Administration to account for temporal variations in natural light conditions. Hourly data on solar azimuth and altitude, measured in degrees and retrieved from SunCalc.org, were used to model the directional behavior and intensity of sunlight, which directly influence shadow effects and light pollution at the study sites.

Population statistics, sourced from Statistics Korea, provided demographic insights into the regional population distribution, which were used to evaluate human exposure to light pollution and shadow flicker. Regional land use data from the National Geographic Information Institute outlined the spatial allocation of urban, agricultural, and conservation areas, offering essential context for assessing the socio-ecological impacts of offshore wind farms.

2.4. Derivation of potential light environmental impact zones

The derivation of the potential light environmental impact zone involves identifying and delineating areas influenced by offshore wind farms during both daytime and nighttime. This process is grounded in the understanding that changes in turbine number, height, arrangement, and distance can significantly affect the light environment, as confirmed by numerous studies (Betakova et al., 2015; Vecchiato, 2014; Kim et al., 2019). The methodology is divided into three key steps: viewshed analysis, shadow impact analysis, and distance analysis. The result of each step is overlaid for deriving potential light environmental impact zones.

2.4.1. Viewshed analysis

The viewshed analysis in this study was conducted to identify the geographical area where offshore wind turbines are visible and assess the degree of potential impacts, such as light pollution and shadow flicker, based on the number of turbines within view (Bishop and Miller, 2007; Sunak and Madlener, 2016). First, this study utilized the "Visibility Analysis" plugin in Quantum Geographical Information System (QGIS) 3.28.1 to perform the analysis. The Visibility Analysis plugin in QGIS is a robust tool for assessing visibility across various landscapes, enabling applications in urban planning, disaster management, and environmental assessments (Horiike et al., 2019; Sahraoui et al., 2018). Its reliability is enhanced by integrating accurate digital elevation models (DEMs), which account for terrain morphology and physical obstacles, ensuring precise calculations (Cillis et al., 2019; Natapov et al., 2024). Continuous improvements through user feedback and usability studies further solidify its effectiveness, making it invaluable for diverse analytical contexts.

Table 1
Dataset collected and utilized in this study.

Category	Data name	Description	Unit	Sources
Geographical data	Digital Elevation Model (DEM)	Terrain elevation data	Meters	National Geographic Information Institute
	Coastline data	Coastline location information	–	National Geographic Information Institute
Wind turbine data	Wind turbine coordinates	Location information for each turbine	Latitude & Longitude	Construction company
	Wind turbine specifications	Turbine model, height, rotor diameter, etc.	Meters	Wind energy database
	Inter-turbine distance	Spacing between turbines	Meters	Construction company
	Number of turbines	Total number of installed turbines	–	Construction company
Environmental data	Sunrise/ sunset times	Sunrise/ sunset times for summer and winter solstices	–	Korea Meteorological Administration
	Solar azimuth and altitude	Hourly solar azimuth and altitude	Degrees	SunCalc.org
Social data	Population statistics	Regional population information	Persons	Statistics Korea
	Land use data	Regional land use status	–	National Geographic Information Institute

Turbine coordinates, derived from CSV files, were used as observer locations, while the turbine heights served as target height values. Second, this study incorporated a 1:5000 scale DEM from the National Spatial Data Infrastructure Portal of South Korea to account for terrain variations. Third, this study set the radius of analysis to 15 km, following previous studies (Betakova et al., 2015; Alphan, 2021) that identified this distance as the threshold at which light-related impacts remain significant. The observer height was defined as 1.7 m, corresponding to the average human eye level according to 2024 Korea National Statistical Office data. The resulting viewshed maps delineated areas within the 15 km radius where turbines are visible and quantified the number of turbines visible at each location.

2.4.2. Shadow impact analysis

The shadow impact analysis in this study was conducted to delineate the spatial and temporal range of shadow flicker, caused by rotating turbine blades obstructing sunlight, which varies based on the sun's direction and angle throughout the day and year. First, this study identified the seasonal extremes of shadow impacts by selecting the summer solstice (longest daylight hours) and winter solstice (shortest daylight hours) in 2023, with date information obtained from the Korea Meteorological Administration (https://data.kma.go.kr). Second, using SunCalc.org, hourly data for the sun's direction and angle were calculated, with horizontal angles of 0° (north), 90° (east), and 270° (west) representing key positions. Third, the "Shadow Depth" feature within the "Terrain Shading" plugin in QGIS 3.28.1 was utilized to analyze the spatial extent of shadow flicker. The "Shadow Depth" feature within the "Terrain Shading" plugin in QGIS 3.28.1 was utilized to analyze the spatial extent and intensity of shadow flicker effects. This plugin has been rigorously tested by the open-source GIS community, which is grounded in the principles of transparency, continuous improvement, and collaborative validation. Open-source development allows for regular updates, community-driven enhancements, and peer feedback, ensuring that tools such as the "Terrain Shading" plugin remain accurate and reliable. Previous studies have validated the accuracy of terrain shading algorithms in similar applications, emphasizing their suitability for environmental studies and planning (Zhang et al., 2020). The input data included a 1:5000 scale DEM of the study area, provided by the National Spatial Data Infrastructure Portal of South Korea, along with turbine specifications such as height and blade length. By integrating these elements, shadow range maps were generated, and exposure duration was quantified to assess the impacts of shadow flicker under both summer and winter solstice conditions.

2.4.3. Distance analysis

The separation distance analysis in this study was conducted to evaluate the relationship between offshore wind turbine distance and its impacts on the light environment, such as visual disturbance and light pollution. First, this study adopted findings from prior studies (Molnarova et al., 2012; Betakova et al., 2015; Peri et al., 2020), which demonstrated that increasing the distance between turbines and observers reduces visual impacts, with meaningful thresholds identified at 2 km, 5 km, and 13 km intervals. Second, this study utilized the Buffer Analysis tool in QGIS 3.28.1 to construct separation distance maps for each study site. Turbine coordinates, derived from CSV files, served as the center points for buffer generation, and distance intervals were defined based on prior literature (Moon et al., 2023; Bishop and Miller, 2007). Third, the resulting buffer zones were analyzed to quantify the spatial extent of visual impacts relative to the coastline and observer positions. By overlaying the separation distance buffers with viewshed and shadow impact data, this study provided an integrated understanding of the light environment's spatial variation.

2.4.4. Overlay analysis for potential light environment impact zones

To select the impact range of the light environment, change at the target site, this study overlaid the viewshed, shadow impact area, and distance from the turbines to derive the impact range of the light environment change at the study site. In this process, this study utilized multi criteria methodology according to the impact levels, and the details of the process can be found in Appendix A. This study then used QGIS classification to reclassify and overlay the values based on the following levels: Low Impact = 1, Medium Impact = 2, and High Impact = 3, with 1 digit for the viewshed, 10 digits for the shadow impact range, and 100 digits for the distance, for a total of 111 to 333 possible values if calculated nested. Namely, 132 means that the area is under low impact of viewshed, high impact of shadow impact, and medium impact of distance.

2.5. Assessment of light environment impact

Light environmental impacts from offshore wind farms bring significant social and ecological challenges. At night, aviation obstruction lights disrupt the nighttime landscape, cause sleep disturbances, and induce psychological stress, with the severity increasing in proportion to the intensity and number of lights (Johansson and Laike, 2007; Pohl et al., 2012). During the day, shadow flicker from rotating turbine blades disrupts daily activities, and prolonged exposure exceeding 30 min can lead to cognitive and physical effects (Freiberg et al., 2019). Ecologically, artificial lighting and shadows disturb wildlife habitats, negatively affecting nocturnal and light-dependent species. Given these impacts, quantitative evaluation and effective mitigation strategies are essential to minimize light environmental impacts. In this context, this study assessed light environmental impacts through two parts as follows: shadow flicker by turbine blade movements and light pollution by turbine's obstruction lights.

2.5.1. Evaluation of shadow flicker

Shadow flicker is a phenomenon caused by the rotating blades of wind turbines intermittently blocking sunlight, resulting in a flickering light and shadow effect (Vision, 2015). First, its intensity diminishes as the distance from the turbines increases, with greater effects observed at higher latitudes, particularly when the sun is low on the horizon (Haac et al., 2022). Second, shadow flicker can cause significant physical and psychological discomfort, necessitating detailed analysis to predict its occurrence and evaluate its impacts during offshore wind farm planning. For this study, the Flicker module in Windpro software developed by EMD International was used to conduct hourly shadow flicker analysis at selected observation points. WindPRO, developed by EMD International A/S, is a comprehensive tool for wind energy project planning, integrating wind resource assessment, energy production estimation, and environmental impact analysis, including noise and shadow flicker simulations. Shadow flicker, caused by turbine blades blocking sunlight, can impact nearby residents. WindPRO's precise simulation module models these effects across seasons and times of day, allowing for optimized turbine placement that minimizes disruptions. By balancing technical efficiency with environmental and social considerations, WindPRO supports the development of sustainable wind energy solutions. Third, as South Korea currently lacks formal guidelines on shadow flicker exposure, this study adopted the World Bank Group's Environmental, Health, and Safety Guidelines (2015), which recommend that exposure should not exceed 30 h per year or 30 min per day under worst-case conditions. The analysis focuses on three predictions: the number of days per year with shadow flicker exposure, the total hours of exposure per year, and the minutes of exposure per day, providing a comprehensive assessment of shadow flicker impacts in the study area.

2.5.2. Evaluation of light pollution

According to the "Standards for Aviation Obstruction Management and Flight Safety Confirmation" from the Ministry of Land, Infrastructure, and Transport, Republic of Korea, aviation obstruction lights are used to inform pilots of obstacles in flight, with the type and number of lights varying based on turbine height and configuration (Appendix B). First, this study identified the coordinates and installation specifications of wind turbines at the project site to calculate the distance and height between turbines. Second, the "Air Obstacle Management and Flight Safety Confirmation Standard" was referenced to determine the expected locations and types of aviation obstruction lights to be installed, as turbines are classified into single or multiple groupings per Article 33, paragraph 5. Third, to assess the visual and environmental impact, a spatial analysis was conducted to predict changes in light intensity (cd/m^2) with distance from the obstruction lights, as light pollution decreases significantly at 1 m and becomes almost negligible beyond 1.5 m (Sullivan et al., 2012; Ford et al., 2017). The results provided a map indicating the location and type of aviation obstruction lights, enabling the prediction of light pollution impact within the affected area.

2.6. Mitigation strategies by landscape planning approaches

To mitigate the light environmental impacts of offshore wind farms, this study synthesizes landscape planning strategies into four targeted approaches. First, turbine placement optimization involves spatial analysis to identify locations where shadow flicker and aviation obstruction lights have minimal overlap with sensitive areas, such as residences and ecological zones. Second, implementing green buffers, such as tree belts or coastal vegetation zones, helps diffuse artificial light and visually integrate turbines into the surrounding landscape. Third, zoning strategies are developed to establish exclusion zones, particularly in visually and ecologically sensitive regions, ensuring controlled turbine placement and minimal intrusion. Fourth, habitat-focused planning prioritizes preserving existing ecological networks and designing wildlife-friendly corridors to mitigate disruptions caused by altered light patterns. These integrated strategies provide a holistic framework for reducing visual and ecological disturbances associated with offshore wind farms while supporting sustainable landscape management.

3. Results

3.1. Zone of potential light environmental impacts

As seen in Fig. 3, the analysis revealed that 8 to 13 turbines are visible in parts of Goi-do, Aphae-do, and Maehwa-do, while 4 to 8 turbines are visible in Unnam-Myeon. However, the western part of Maehwa-do showed no turbine visibility due to the area's mountainous geographical characteristics. In Aphae-do, 4 to 8 turbines are visible in the northern region, where mountains limit visibility, whereas the southern part, adjacent to the sea, shows 8 to 13 visible turbines. This southern region, with a higher population density and economic activity, is likely to experience greater impacts on the light environment caused by turbine visibility. In contrast, while Goi-do also has residents near the sea, the presence of mountains in front of most residences is expected to mitigate visibility impacts. For Unnam-Myeon and Maehwa-do, high visibility impacts were identified in areas adjacent to the sea; however, as these regions are primarily agricultural areas focused on rice production, the impacts on human activity are expected to be minimal.

The shadow depth technique was applied to analyze the expected shadow impact range, using parameters such as sun angle and turbine specifications. The analysis showed that turbines WTG#11–13 affect parts of southern Unnam-Myeon and Maehwa-do, located south of the offshore wind farm center, with additional partial impacts caused by WTG#5 and WTG#6. For Goi-do and Aphae-do, no direct shadow impacts were identified, although some shadow effects were observed due to the islands' topographic characteristics. While shadow exposure exceeding 6 h per day can significantly affect human activities, the impacts in these areas were found to be insignificant.

Shadow flicker caused by turbine blade movement can negatively affect humans, with severity increasing closer to residential areas (McCunney et al., 2014; Haac et al., 2022). A study analyzing residents' perceptions of offshore wind landscapes across 1, 3, 5, and 12 km distances revealed that negative perceptions were highest at 1 km, moderate at 3 km, and low at 5 and 12 km (Moon et al., 2023). In the case of Aphae-do, which lies within 2 km of the power complex, significant impacts were identified, necessitating mitigation measures for this area. Other high-population zones are located at moderate distances of 5 to 13 km, except for some coastal regions adjacent to the turbines.

Fig. 3 shows the results of the three previous analyses, which are overlaid to derive the target area of impact. The coastal area southwest of Maehwa-do, the coastal area north of Aphae-do, and some areas south of Goi-do and Unnam-Myeon were determined to be strongly affected and grouped into the 311 to 313 classes due to their proximity to the offshore wind farm. Notably, the distance from the turbines is less than 2 km, the shadow effect is less than 3 h/day, and 1 to 13 turbines are within the local viewshed, which means that the visual impact is high. Areas assessed to be affected by turbines and grouped into classes 211 through 233 are 2 and 5 km from the turbines. The shadow effect ranges from 0 h to more than 6 h per day, and the viewshed includes between 1 and 13 units, indicating moderate visual impact. Areas grouped into classes 111 through 133 are more than 5 km but less than 13 km from turbines; the shadow effect is less than 0 h and more than 6 h per day, and the viewshed includes 1 to 13 units, indicating a low visual impact. Through this comprehensive overlay analysis, the zone of potential light environmental impact was derived.

Using the DEM data from the project area, the spatial extent of the visibility of offshore wind turbines at an observer's eye level (1.7 m) was derived. The analysis revealed that the number of visible turbines correlates directly with the potential impact: the greater the number of

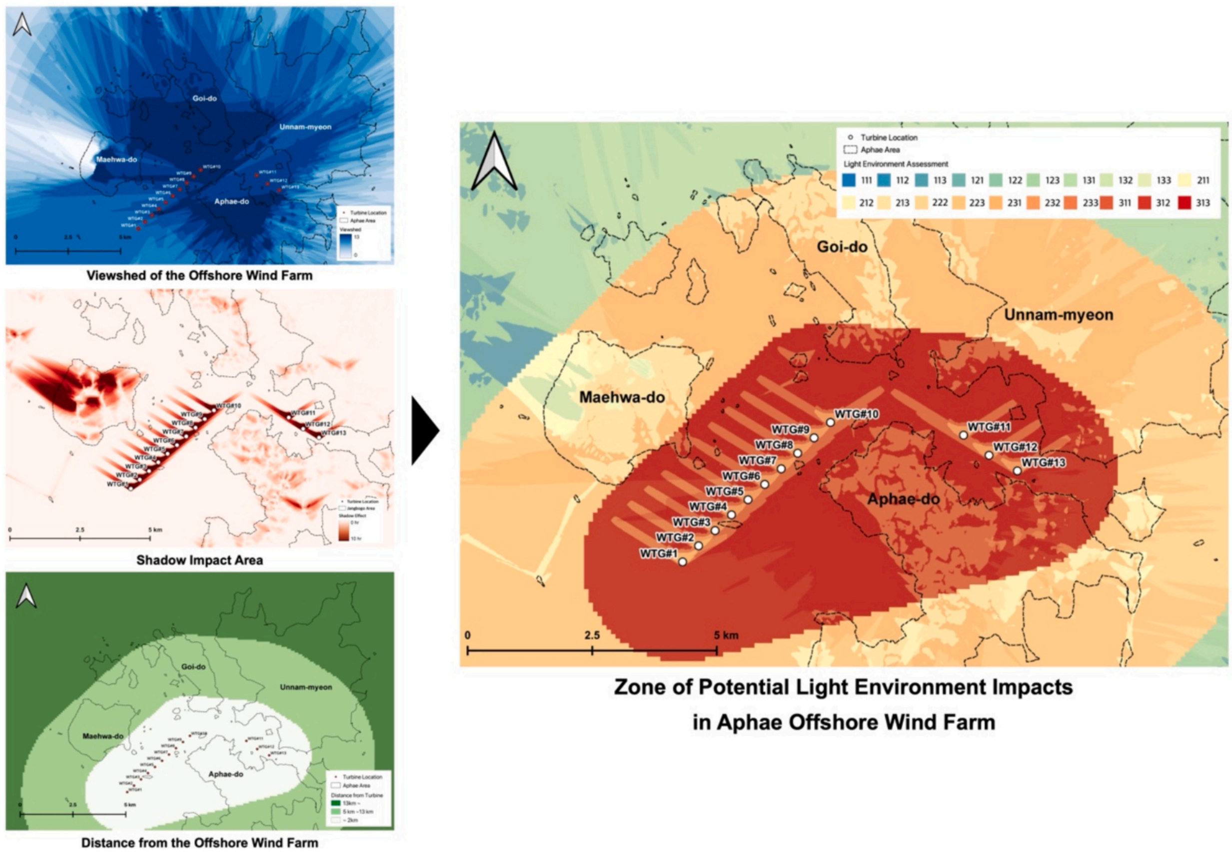


Fig. 3. Potential light environment impact zone in Aphae offshore wind farm.

turbines in view, the higher the impact. The results indicated that the number of visible turbines is high east of Cheongsan-do, south of Deokwoo-do, and throughout Hwangjae-do. In the eastern part of Cheongsan-do, where the entire offshore wind farm is visible, the impact remains minimal due to mountainous terrain. However, in some inland areas of Cheongsan-do, approximately 30 turbines are visible, and as the area includes inhabited zones and recreational facilities such as Shinheung Beach, mitigation measures for tourists are necessary. In southern Pyeongil-do, about 10 turbines are visible due to the unobstructed view from the southern coastal area. In Saengil-do, turbines are partially visible from residential areas. For Deokwoo-do, while approximately 50 turbines are visible in the southern part, residential zones are shielded by mountains, resulting in negligible impact. In contrast, Hwangjae-do, the closest urban area to the offshore wind farm, experiences full visibility of the turbines from its western side, necessitating mitigation measures for its large residential population.

The shadow impact analysis, conducted using the shadow depth technique, incorporated parameters such as sun angle and turbine specifications (height, blade diameter, and rotational area). The results showed that Cheongsan-do, Deokwoo-do, and Hwangjae-do—all located closest to the wind farm—fall outside the shadow effect zone at sea. However, Hwangjae-do is located between 5 km and 13 km from the turbines and, as a residential and tourist area, is expected to have a moderate negative perception, requiring mitigation measures. In Deokwoo-do, the southern areas lie within the 5–13 km range, but the residential zones are farther than 13 km, which limits potential negative perceptions. In Saengil-do and Pyeongil-do, only the southern areas are within the 13 km impact zone, with minimal visibility and low overall impact. For Cheongsan-do, although the island is within the 13 km range, the western part is shielded by mountainous terrain, whereas the eastern part, where the entire offshore wind farm is visible, experiences significant visual impacts.

Fig. 4 illustrates the overlay of the three light-related factors—viewshed, shadow effect area, and distance—used to derive the light environment impact range. Compared to the Aphae Offshore Wind Farm, the Wando Jangbogo Offshore Wind Farm has limited impacts on local residents due to its offshore location. In Deokwoo-do, the southern area was classified into classes 211 to 232, with distances ranging from 2 to 5 km, shadow effects from 3 to 6+ hours/day, and visible turbines numbering 0 to 35, indicating a moderate visual impact. Saengil-do was categorized into class 111, with distances between 5 and 13 km, shadow exposure under 3 h/day, and fewer than 17 turbines visible, resulting in insignificant visual impact. Most of Cheongsan-do fell into the insignificant visual impact class (111) due to its mountainous topography, though inland areas with tourist facilities were grouped into classes 131 to 133, requiring mitigation measures for light pollution from aviation obstruction lights. The western part of Hwangjae-do, classified into classes 233 to 313, experiences significant changes in the light environment due to its proximity to turbines and residential population, necessitating targeted mitigation strategies. Through this comprehensive overlay analysis, the zone of potential light environmental impact was derived.

The analysis revealed that the frequency of turbine visibility is high in Yeongdo-gu, Seo-gu, Saha-gu, Gangseo-gu, and Gadeokdo Island, areas located close to offshore wind turbines. In Yeongdo-gu, where natural tourist attractions such as beaches, coastal trails, and observatories are situated, the entire offshore wind farm is visible, resulting in a high impact of light pollution on tourists and local residents. Similarly, in the southern part of Seo-gu, the wind farm is visible from coastal parks and observatories, projecting significant light pollution impacts on tourists and residents. In Saha-gu, the entire offshore wind farm is visible from Dadaepo Beach and nearby residential areas to the south, while other residential areas experience lower impacts (fewer than 4 turbines visible) due to forested areas obstructing visibility. In Gangseo-gu,

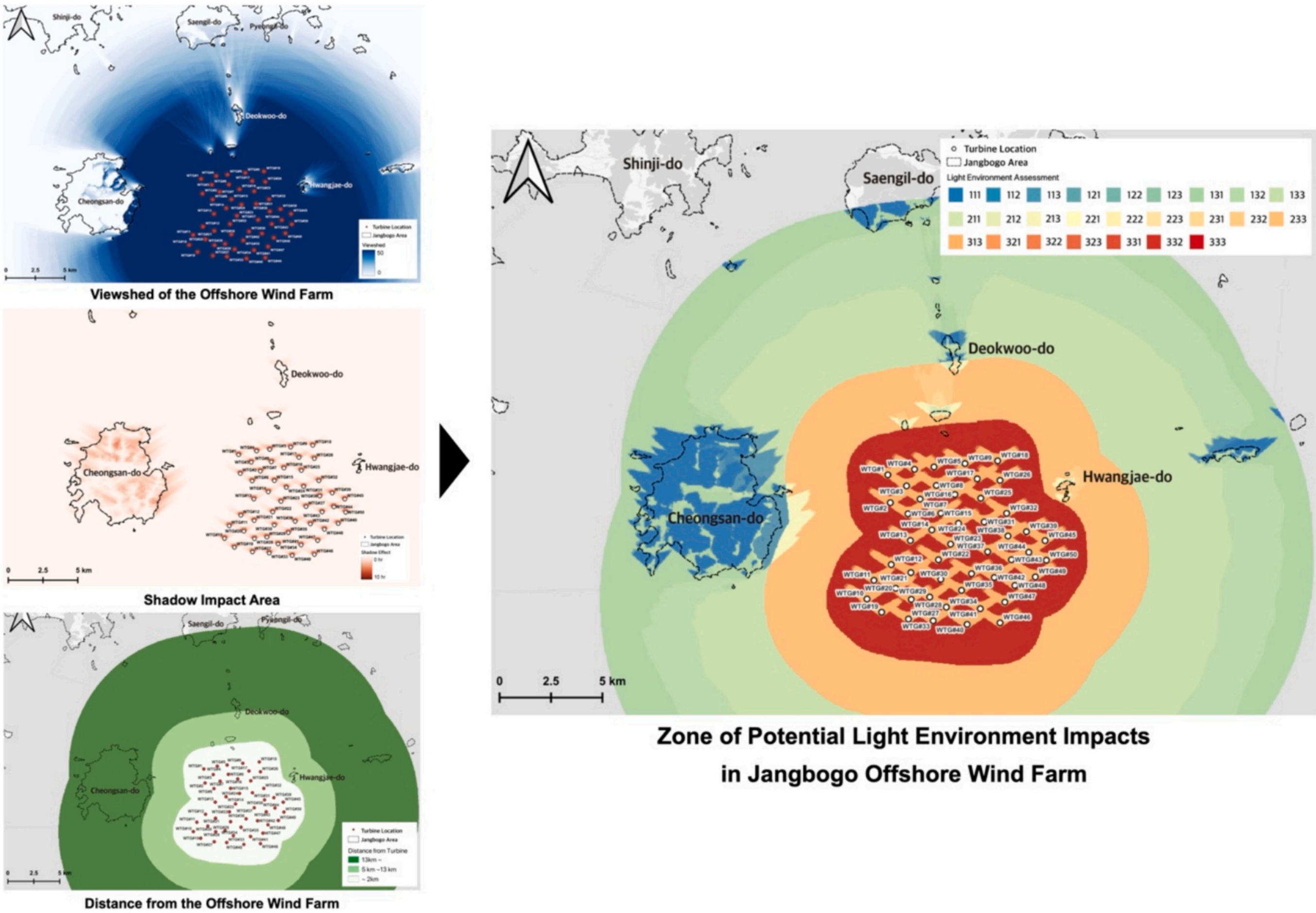


Fig. 4. Potential light environment impact zone in Jangbogo offshore wind farm.

where residential zones are located adjacent to the sea, visibility of the entire offshore wind farm is expected to cause significant changes in the light environment for local residents.

Eulsukdo Island, located between Gangseo-gu and Saha-gu, lies along the migratory route of birds traveling between East Asia and Australia and is a critical ecosystem conservation area. Despite its ecological significance, 6 to 12 turbines are visible, posing risks such as disturbances to migration routes, spawning grounds, and potential impacts on bird populations. Conversely, in eastern Gadeokdo Island, although the offshore wind farm is entirely visible, the area is predominantly forested, minimizing impacts on local residents.

The shadow depth technique was applied to predict the shadow effect of 12 turbines. The results showed that most of the study area lies outside the shadow effect zone, except for turbines WTG#8–11, which produce shadow flicker for approximately 2–3 h daily in the southern part of Saha-gu, where Molundae Amusement Park and Molundae Observatory are located. These popular tourist spots are visited frequently, necessitating mitigation plans to reduce the shadow effects. The Molundae Observatory, located within 2 km of the turbines, was identified as highly impacted, with a strong likelihood of negative perceptions among tourists. Saha-gu and parts of Seo-gu located at distances between 5 and 13 km were found to be moderately affected, particularly in coastal parks and fishing zones, where residents and tourists are likely to perceive negative impacts.

Fig. 5 presents the overlay results of the three light-related factors—viewshed, shadow effect area, and separation distance—to derive the zone of potential light environmental impact. The Busan Dadaepo Offshore Wind Farm site is characterized by its nature-centric tourism and high cultural value, with frequent traffic from tourists and residents. Notably, areas such as the Molundae Observatory and Molundae Amusement Park were classified into classes 312–332, where distances are less than 2 km, shadow effects range from less than 3 to more than 6 h/day, and between 4 and 8 turbines are visible. These findings indicate a high visual impact, requiring targeted mitigation measures. In the area behind Molundae Observatory, including Dadaepo Beach, the impact is classified as 232, with a distance of 2–5 km, shadow effects exceeding 6 h/day, and visibility of 4 to 8 turbines, representing moderate visual impact.

The southern Seo-gu region, with industrial facilities and tourist spots, was classified into classes 212 and 233, where distances range from 2 to 5 km, shadow effects exceed 6 h/day, and visibility ranges from 8 to 12 turbines, indicating moderate impacts. Gangseo-gu and Eulsukdo Island were classified as 133, with distances of 5–13 km, shadow effects exceeding 6 h/day, and visibility of 8 to 12 turbines, resulting in low visual impact. Lastly, most of Gadeokdo Island and Yeongdo-gu were classified into class 113. While the mountainous terrain in Gadeokdo limits visual impacts, Yeongdo-gu, as a residential and tourist zone with beaches and observatories, requires targeted mitigation strategies to reduce the adverse effects of changes in the light environment. Through this comprehensive overlay analysis, the zone of potential light environmental impact was derived.

3.2. *Light environmental impacts*

3.2.1. *Shadow flicker*

The shadow flicker analysis across the three offshore wind farms—Aphae, Jangbogo, and Dadaepo—reveals distinct variations in exposure levels depending on proximity to turbines and the landscape

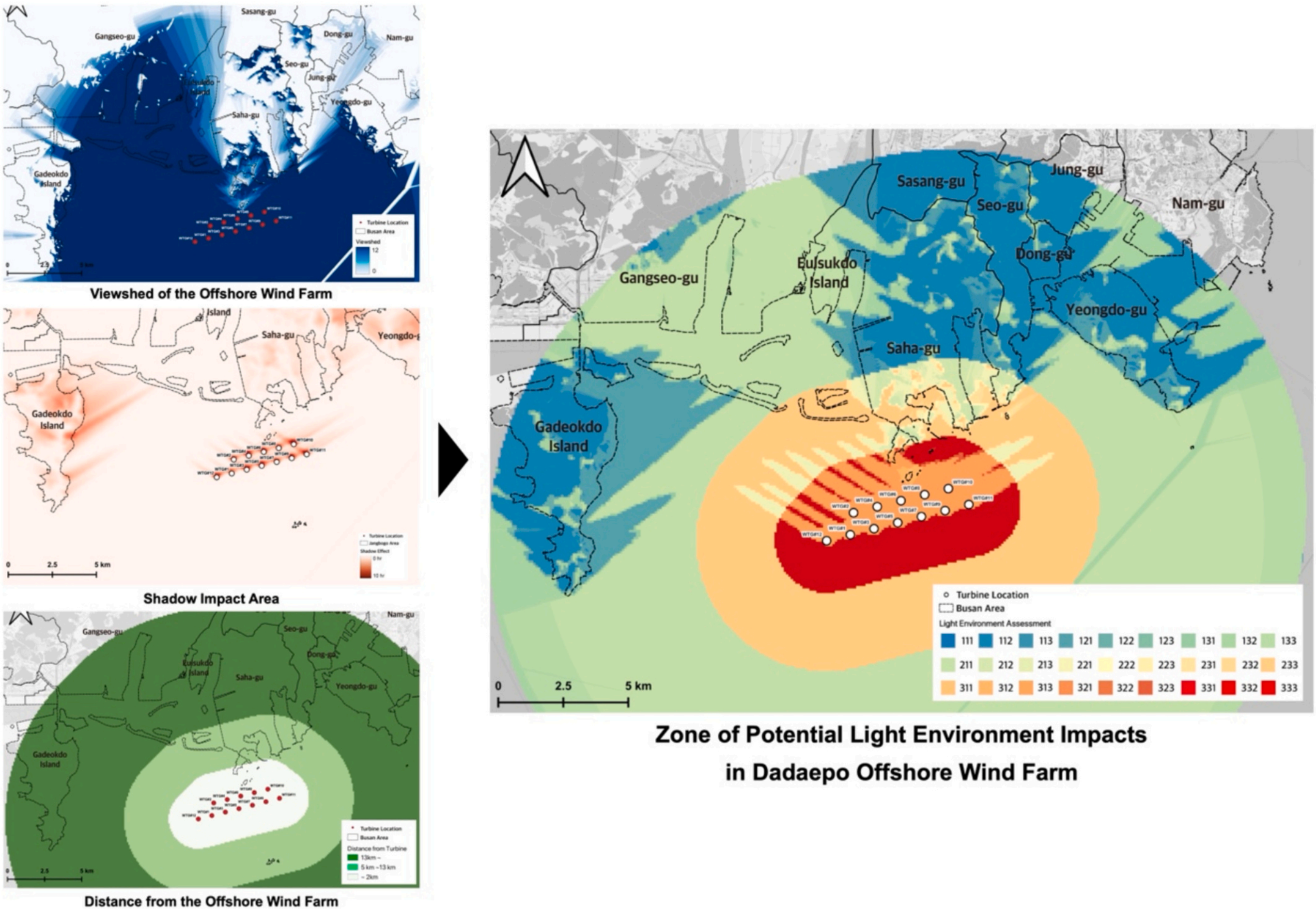


Fig. 5. Potential light environment impact zone in Dadaepo offshore wind farm.

characteristics of each site (Fig. 6).

At the Aphae Offshore Wind Farm, shadow flicker exposure was the most significant due to the site's proximity to populated and coastal areas. The northern coastal region of Aphae-do, closest to the turbines, experienced the highest levels of exposure, with shadow flicker predicted for up to 154 days per year (Fig. 6A-1). Similarly, the southern coastal area of Unnam-Myeon showed exposure for up to 127 days annually, with localized zones reaching 155 days. In the southeastern coastal area of Maehwa-do, shadow flicker occurred for up to 71 days per year. In terms of annual hours of exposure, the inland region north of Aphae-do was the most affected, with shadow flicker lasting up to 79 h per year, while the southern coastal area of Unnam-Myeon experienced 22 h annually, and Maehwa-do recorded lower exposure of 3 h per year (Fig. 6A-2). Daily shadow flicker exposure also varied significantly, with the northern part of Aphae-do recording up to 39 min per day, while Maehwa-do and Unnam-Myeon experienced up to 36 min per day, with localized coastal zones reaching 40 min. In contrast, Goi-do remained entirely unaffected across all scales of analysis (Fig. 6A-3).

In the Jangbogo Offshore Wind Farm, shadow flicker impacts were negligible due to the site's island landscape and greater separation distances between the turbines and populated areas. Areas adjacent to the power complex, including Cheongsan-do, Deokwoo-do, and Hwanghae-do, showed no shadow flicker exposure. Likewise, the regions of Shinji-do, Saengil-do, and Pyeongil-do within the project area were unaffected. The results confirm that all areas around the Jangbogo project site complied with the World Bank Group (2015) guidelines, which limit shadow flicker exposure to 30 h annually and 30 min daily (Fig. 6B-2, B-3).

At the Dadaepo Offshore Wind Farm, moderate shadow flicker impacts were observed, particularly in urban and recreational zones located close to the turbines. Areas within 2 to 5 km of the turbines, such as Saha-gu and the southern part of Seo-gu, experienced shadow flicker exposure, with notable impacts in locations like Molundae Observatory and Dadaepo Beach. However, the analysis confirmed that all areas surrounding the Dadaepo project site met the World Bank Group (2015) targets of 30 h annually and 30 min daily, while regions beyond 5 km experienced negligible or no shadow flicker impacts (Fig. 6C-2, C-3).

In summary, the shadow flicker analysis highlights that the Aphae Offshore Wind Farm exhibited the most significant exposure, particularly in Aphae-do, Unnam-Myeon, and Maehwa-do, due to their proximity to turbines. In contrast, the Jangbogo Offshore Wind Farm showed no measurable impact, benefitting from greater separation distances and the natural buffering effect of the island landscape. The Dadaepo Offshore Wind Farm displayed moderate impacts, particularly in urban areas with higher population density and recreational activity. These findings underscore the need for targeted mitigation measures in highly affected regions such as Aphae and Dadaepo to minimize the effects of shadow flicker exposure.

3.2.2. *Light pollution*

According to the "Standards for Aviation Obstacle Management and Flight Safety Confirmation" promulgated by the Ministry of Land, Infrastructure, and Transport of the Republic of Korea, the aviation obstruction lights required for installation at the project sites were evaluated for three wind turbine models: MySE6.45-180 at the Aphae Offshore Wind Farm, DS205-8MW at the Jangbogo Offshore Wind Farm, and EW8.5-230 at the Dadaepo Offshore Wind Farm. The MySE6.45-180 model, with a total height of 207.8 m, and the DS205-8MW model, with

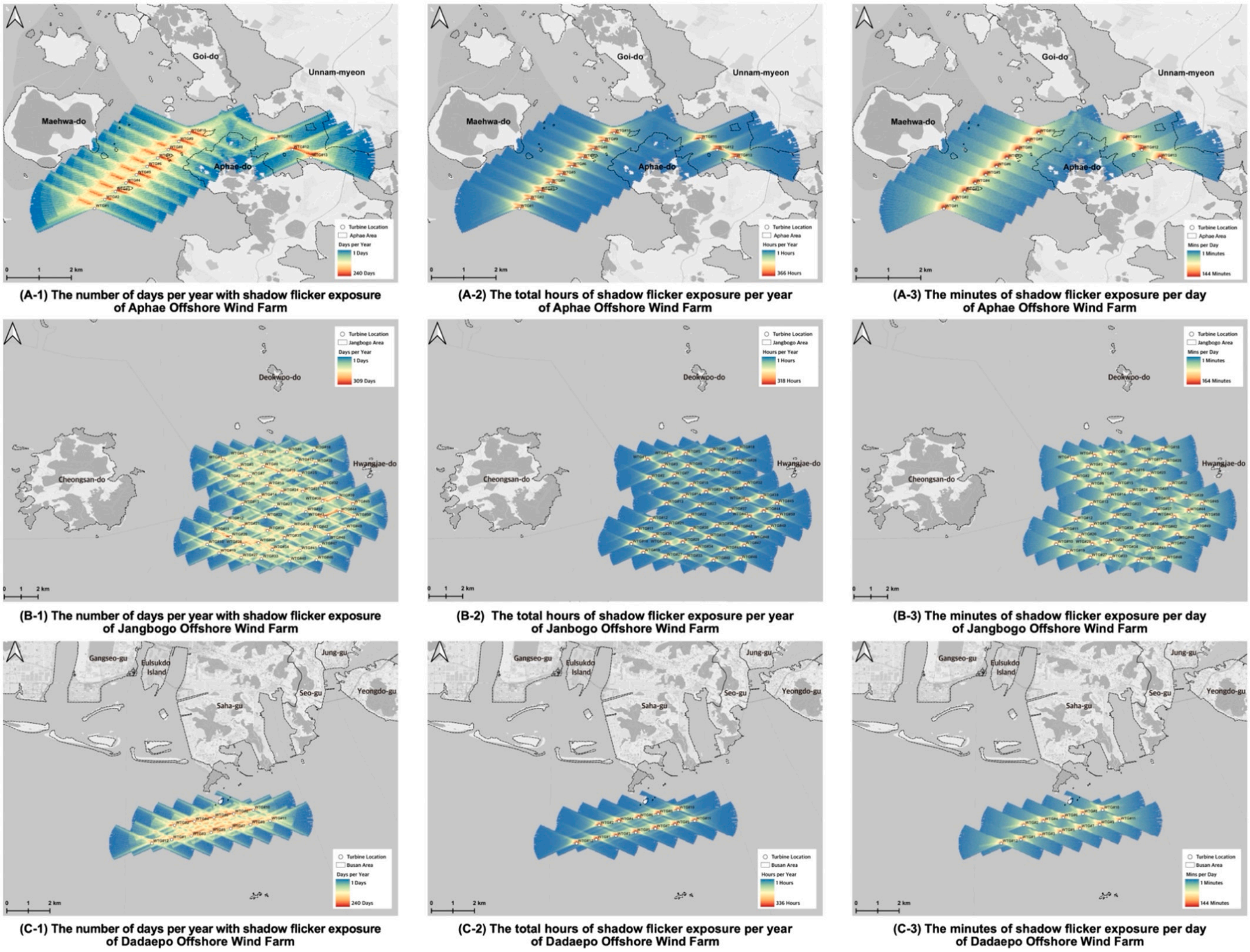
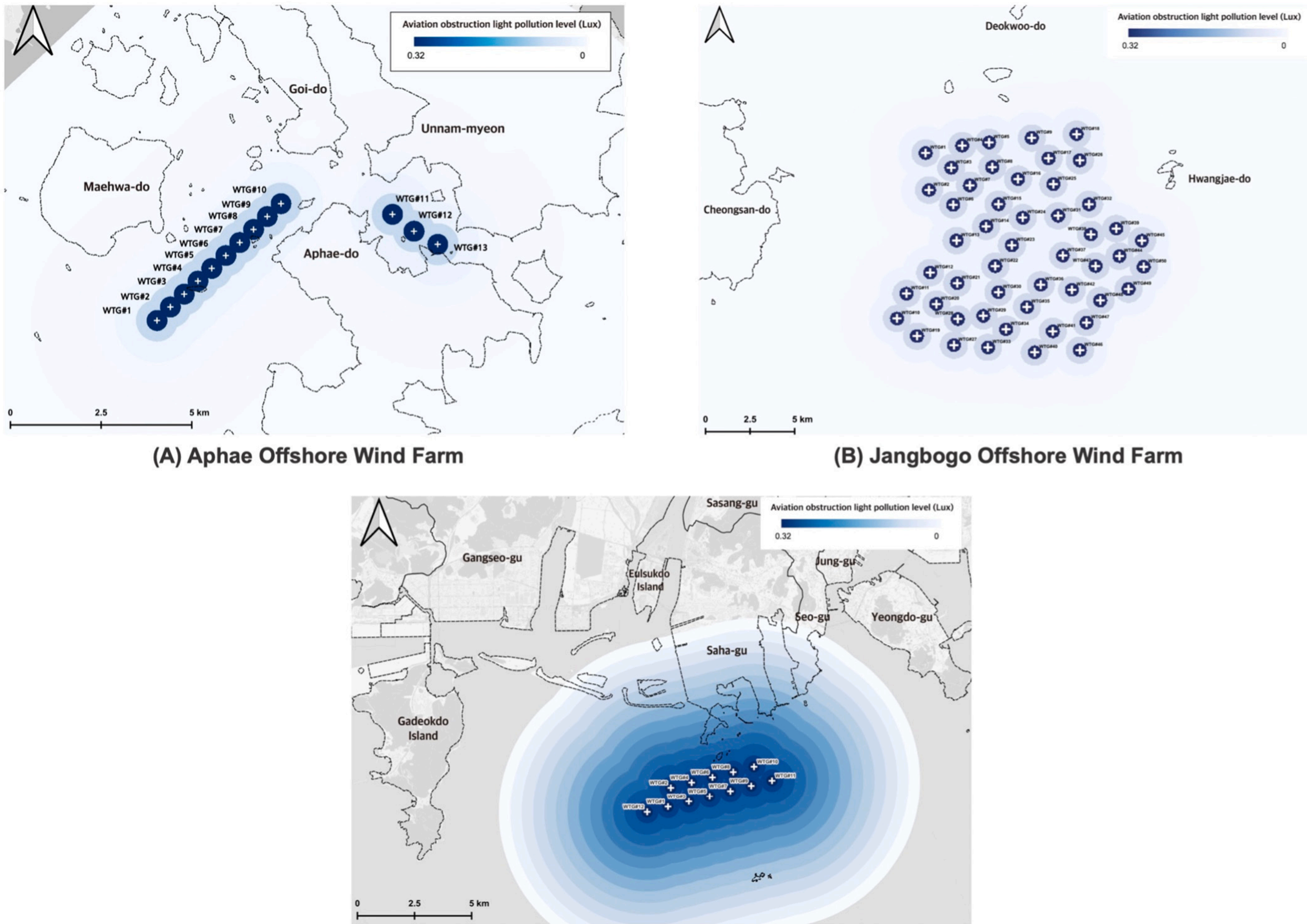


Fig. 6. Potential light environment impact zone in Dadaepo offshore wind farm.

a height of 232 m, require the installation of two medium A-, B-, or C-type obstruction lights at the top of the turbine to ensure visibility to pilots from any direction. Similarly, the EW8.5-230 model, standing at 240 m, also requires the installation of two medium A-, B-, or C-type lights. For all three turbine models, it is critical that the lights are positioned to prevent mutual interference with each other's output. Additionally, a minimum of three low E-type lights must be installed at a midpoint between the ground and the nacelle for all turbine models to comply with aviation safety standards. While the general requirements for medium and low lights remain consistent across all three turbine models, the installation heights vary slightly due to differences in the total turbine height.

The comparison of aviation obstruction light impacts across the Aphae, Jangbogo, and Dadaepo Offshore Wind Farms reveals variations in turbine spacing, rotor diameter, and resulting light pollution intensities based on proximity to the turbines (Fig. 7). Light pollution is inversely proportional to the square of the distance, and the starting luminance for medium-intensity Type A lights is 20,000 lx, which rapidly decreases with increasing distance (Ford et al., 2017). The Aphae Offshore Wind Farm consists of 13 turbines arranged in a linear array with spacing between 1246 and 1780 m for a rotor diameter of 178 m (Fig. 7A). Light pollution begins at 0.02 lx during daylight and dusk and rapidly decreases to 0.005 lx at 2 km. While most of the project area is more than 2 km away, the northern coastal area of Aphae-do, particularly near WTG#12–13, experiences elevated light pollution levels between 0.32 and 0.08 lx, necessitating mitigation strategies due to its proximity to residential and work areas. The Jangbogo Offshore Wind Farm features 50 turbines with spacing between 1435 and 2050 m for a rotor diameter of 205 m. The light intensity profile is similar, starting at 0.02 lx and dropping to 0.005 lx at 2 km. However, most of the project area is located more than 5 km from the turbines, where light intensity falls well below 0.002 lx. Consequently, the light pollution impact in the Jangbogo project area is considered insignificant. The Dadaepo Offshore Wind Farm, with 12 turbines spaced between 1610 and 2300 m for a rotor diameter of 230 m, exhibits a similar light pollution pattern. Areas such as Saha-gu and the southern Seo-gu region, located within 2 to 5 km, are exposed to light intensities between 0.005 and 0.0008 lx, indicating moderate impacts. Beyond 5 km, light intensities drop below 0.002 lx, and impacts become negligible.

The degree of aviation light pollution can vary depending on landscape types. The Aphae Offshore Wind Farm, situated in a rural landscape, experiences the highest localized light pollution due to its proximity to residential and working areas, particularly in the northern coastal zone near the eastern turbines. In contrast, the Jangbogo Offshore Wind Farm, located in an island landscape, shows the lowest impact, as most of the project area is situated more than 5 km from inhabited zones (Fig. 7B). The island's natural topography and sparse population further act as buffers, mitigating light pollution. The Dadaepo Offshore Wind Farm, positioned in urban landscapes, exhibits moderate impacts, particularly in Saha-gu and the southern Seo-gu



(C) Dadaepo Offshore Wind Farm

Fig. 7. Light pollution by offshore wind farms.

region, where residential zones and recreational sites, such as Dadaepo Beach and Molundae Observatory, lie within 2 to 5 km of the turbines (Fig. 7C). These findings highlight those areas with higher population density and proximity to turbines, such as rural coastal landscapes like Aphae and urban landscapes like Dadaepo, require targeted mitigation measures to minimize light pollution effects. In contrast, island landscapes like Jangbogo benefit from greater separation distances and natural topographical buffers, resulting in minimal light pollution impacts.

4. Discussion

4.1. Optimized turbine placement

The results reveal that shadow flicker impacts are most pronounced in rural coastal landscapes such as the Aphae Offshore Wind Farm, where turbines are located in close proximity to residential and working areas. The northern coastal regions of Aphae-do and parts of Unnam-Myeon experienced shadow flicker for up to 154 days per year and 39 min per day, exceeding acceptable exposure thresholds. In these areas, where high-intensity agricultural activities are prevalent, shadow flicker can disrupt agricultural workers' daily routines, particularly during peak working hours. This issue is compounded by the region's aging population, which is more vulnerable to stress caused by prolonged exposure to shadow flicker. To mitigate such issues, turbine placement must be optimized to minimize shadow flicker in sensitive areas. Strategic positioning of turbines, maintaining a minimum 2–5 km separation distance from residential and agricultural zones, and avoiding alignment near ecologically vulnerable areas such as coastal wetlands can significantly reduce shadow flicker exposure (Betakova et al., 2015; Haugen, 2011). Additionally, curtailing turbine operations during high-sun-angle hours (sunrise and sunset) can alleviate flicker effects during periods of maximum human activity (Haac et al., 2022). These measures are particularly relevant for rural coastal areas, where human activities and well-being are closely tied to natural and working landscapes.

4.2. Green infrastructure

In urban landscapes such as the Dadaepo Offshore Wind Farm, shadow flicker impacts are moderate, particularly in recreational areas like Molundae Observatory and Dadaepo Beach, which are located within 2–5 km of the turbines. These locations are heavily frequented by tourists and residents, making visual and shadow disturbances a significant concern. Implementing green infrastructure solutions such as tree belts, vegetated buffers, and coastal vegetation zones can effectively mitigate these impacts. Vegetation buffers can act as natural screens, diffusing the intensity of shadow flicker and softening the visual impact of turbines (Hamling, 2024; Gan et al., 2023). In addition to reducing visual disturbances, green infrastructure provides ecological benefits, such as creating habitats for urban wildlife and enhancing local biodiversity. For instance, reforesting urban-adjacent areas near Dadaepo Beach would not only improve the aesthetic quality for visitors but also support migratory bird habitats, particularly in ecologically sensitive areas like Eulsukdo Island, where migratory routes must be preserved.

Such integrated green infrastructure strategies ensure that visual comfort for tourists and ecological integrity are maintained while enhancing the overall sustainability of urban-tourism landscapes.

4.3. Zoning regulations

The Jangbogo Offshore Wind Farm, located in an island landscape, exhibited minimal shadow flicker impacts due to the greater separation distances from populated zones and the natural topographical buffers provided by surrounding islands such as Cheongsan-do and Deokwoo-do. This underscores the effectiveness of zoning regulations that prioritize turbine placement in low-population-density areas and ecologically insensitive zones. For tourism-dependent areas such as Cheongsan-do, where natural scenery is a key attraction, regulatory frameworks should enforce exclusion zones near beaches and observatories to protect visual aesthetics and reduce shadow flicker impacts. In addition, nighttime glare from aviation obstruction lights can be minimized through the shielding and directional adjustment of lights, ensuring compliance with visibility standards while reducing unnecessary disturbances (Falchi et al., 2019). The zoning strategies for island landscapes not only preserve the natural beauty that supports tourism but also protect vulnerable ecosystems from cumulative impacts caused by offshore wind development.

4.4. Habitat preservation and restoration

Shadow flicker and turbine presence in offshore wind farms can pose ecological challenges, particularly in areas adjacent to critical wildlife habitats. In the Aphae Offshore Wind Farm, where shadow flicker impacts are prolonged in coastal agricultural zones, there is an increased risk of disrupting species' natural behaviors, such as migration patterns and circadian rhythms (Chen and Dong, 2023). Habitat preservation and restoration efforts, such as protecting coastal wetlands and reestablishing natural vegetation buffers, can significantly mitigate these disturbances. For example, restoring vegetative zones in Maehwa-do and Unnam-Myeon would not only reduce flicker exposure but also provide ecological resilience to vulnerable habitats.

In island landscapes such as Jangbogo Offshore Wind Farm, preserving biodiversity hotspots like migratory bird pathways is essential. Establishing wildlife corridors and no-development zones ensures that habitats remain connected and undisturbed, preventing disruptions to migration routes and breeding grounds. In urban-adjacent ecologically significant areas like Eulsukdo Island near the Dadaepo Offshore Wind Farm, implementing radar-activated aviation lights that operate only when necessary can minimize light disturbances to wildlife (Department of Climate Change Energy the Environment and Water, 2023). Aligning such measures with global conservation efforts further ensures the long-term protection of critical ecosystems and enhances the ecological sustainability of offshore wind projects.

5. Conclusion

Offshore wind power projects play a critical role in achieving South Korea's renewable energy targets and addressing global climate goals. This study introduced a quantitative evaluation methodology to assess the impacts of light pollution from aviation obstruction lights and shadow flicker caused by turbine blade movement in newly constructed offshore wind farms. By applying advanced tools such as QGIS and windPRO software, the study analyzed the impacts on urban, rural, and island landscapes across three major offshore wind farm sites: Aphae, Jangbogo, and Dadaepo. The results demonstrated that areas in close proximity to wind turbines—particularly rural coastal zones such as Aphae-do and recreational urban areas like Dadaepo—experience significant impacts. In contrast, island landscapes like Jangbogo exhibited minimal effects due to greater separation distances and natural topographical buffers. These findings highlight the need for targeted mitigation strategies, including optimized turbine placement, green infrastructure solutions, zoning regulations, and habitat preservation, to effectively minimize the adverse effects of light pollution and shadow flicker.

This study provides valuable insights into the multifaceted impacts of offshore wind farms, particularly focusing on their effects on both human well-being and ecological systems. While the integration of spatial analysis tools and environmental modeling enabled a comprehensive assessment, several limitations exist. The study did not measure the subjective perceptions and psychological effects of local communities directly, and it relied on static data inputs that may not fully reflect dynamic environmental conditions or evolving community acceptance. Additionally, one limitation of this study was the inability to analyze the lateral and vertical distribution dynamics of light pollution, as the WindPRO software used primarily focused on wind energy project analysis and lacked specific functionality for such evaluations. Furthermore, the focus on South Korean offshore wind farms limits the generalizability of the findings to regions with differing socioecological and policy contexts.

Future research should address these limitations by incorporating qualitative methods such as surveys and interviews to capture community perceptions and psychological impacts. Integrating real-time environmental data—including wind speed, sun position, and atmospheric conditions—would improve the accuracy of predictions for light pollution and shadow flicker. Additionally, exploring the cumulative impacts of multiple offshore wind farms on marine ecosystems and avian migration routes will be critical for developing comprehensive ecological protection plans. Finally, applying this methodology to global offshore wind farm projects will provide comparative insights, fostering a more robust understanding of impacts across various landscapes and cultural settings.

CRediT authorship contribution statement

Min Kim: Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization, Data curation, Writing – original draft, Formal analysis. **Hojun Choi:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Writing – review & editing. **Jinhyung Chon:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization, Writing – original draft.

Declaration of competing interest

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

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Appendixes. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.117718.

Data availability

The authors do not have permission to share data.

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