

Evaluating the effectiveness of EIA review for onshore wind power projects in South Korea using multi-criteria analysis

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ARTICLE INFO

Keywords:

Effectiveness evaluation framework
Environmental assessment index (EA-index)
Environmental quantification tool
Renewable energy projects
Sustainable development

ABSTRACT

Environmental Impact Assessment (EIA) systems play a crucial role in systematically reviewing and analyzing the potential environmental impacts of development plans, contributing significantly to environmental conservation. However, there is a growing demand to evaluate the practical effectiveness of EIA. This study introduces a novel quantitative assessment of EIA effectiveness, in contrast to the traditionally used qualitative approaches. A data-driven framework was employed to provide an objective measurement of environmental performance improvements before and after the EIA review. The overall objective of this study was to quantitatively evaluate the effectiveness of the EIA review process for onshore wind power projects (WPPs) in South Korea over the last decade (2013–2022) using an Environmental Assessment Index (EA-Index) based on a multi-criteria analysis. The EA-Index, comprising 23 indicators in three components (natural environment, resource conservation, and living and social environment), weighted by the Analytic Hierarchy Process (AHP), provides a structured and objective method to measure environmental performance before and after an EIA review. The results showed a general improvement in environmental performance post-approval, with the average EA-Index for 79 WPPs increasing from 105.4 to 117.9 and success rates exceeding the reference value of 100 increasing from 60.8 % to 74.4 %. This improvement was driven by significant increases in the indicators within the natural environment. The significant improvements observed from 2017 to 2020 reflect the impact of the revised EIA guidelines and stricter evaluation criteria. This study highlights the need for tailored EIA guidelines to address site-specific characteristics, enhanced stakeholder engagement, and continuous policy refinement to support sustainable development. The EA-Index proved to be a robust tool for evaluating EIA effectiveness, providing critical policy implications and recommendations.

1. Introduction

The Environmental Impact Assessment (EIA) system in South Korea was first conceptualized with the enactment of the Environmental Conservation Act in 1977 and has been fully implemented since 1981, spanning over 40 years of practice. Throughout this period, the EIA functioned as a critical tool for environmental conservation, systematically reviewing and analyzing the potential environmental impacts of development projects. By identifying and mitigating adverse effects in advance, the EIA process facilitates informed and balanced decision-making that strives to achieve harmonious integration of development and environmental conservation (Korean Society of Environmental Impact Assessment (KSEIA), 2022).

However, although the implementation of the EIA system has

generally been positively perceived in terms of its intent and objectives, there is a growing demand for a more detailed analysis of its effectiveness. In certain cases, the effectiveness of the EIA, particularly concerning projects that have become social issues, has been questioned (Kim et al., 2016). Consequently, there has been criticism that the EIA system is merely being used as a tool for verifying rationality. In other words, it is becoming increasingly important to assess whether EIA is being properly implemented in alignment with its objectives, and to determine its effects on both environmental and social aspects.

The assessment of EIA effectiveness is gaining attention because EIA is sometimes perceived as an obstacle to development owing to its stringent participation process and the requirement for scientific investigations. This perception can lead to the view that EIA is excessively time-consuming and costly (Bond et al., 2012; Runhaar et al., 2014).

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Additionally, there are general and ongoing international concerns about the efficiency, quality, and effectiveness of EIA systems. Therefore, the analysis, evaluation, and discussion of EIA effectiveness are considered important topics in EIA-related research (Sadler, 1996; Lawrence, 1997; Cashmore, 2004; Elling, 2009; Morgan, 2012; Rozema and Bond, 2015; Pölonen et al., 2018).

Several studies have been conducted to develop and refine tools for evaluating the effectiveness of EIA. Alberts et al. (2020, 2021) evaluated EIA effectiveness in protected areas in South Africa using 42 key performance indicators derived from a theory of change approach. The study emphasized the need to strengthen the EIA as a policy tool for decision-makers due to increasing international pressure on development within protected areas. Effective EIA contributes to socioeconomic development within protected areas, while underscoring the role of EIA for future generations. Based on the findings of this study, the development of EIA guidelines, education, and flexible procedures to enhance the effectiveness of EIA in protected areas were proposed.

Li et al. (2023) analyzed global trends and key themes in EIA based on over 4000 literature sources and evaluated the effectiveness of EIA for industrial complex construction projects in the northeastern region of China based on practical experiences. In their study, a quantitative evaluation based on EIA stage-specific indicators was conducted, along with a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis to identify the internal strengths and weaknesses and external opportunities and challenges of the EIA. This approach was used to propose future development strategies for the EIA of complex industrial projects in northeastern China.

Yoo et al. (2010, 2011) conducted studies on the comprehensive environmental impact assessment index (CEIAI) for development projects in South Korea, establishing a framework for the principles and strategies in index calculation, and proposing factors that can serve as indicators of environmental impacts. These indicators were approached from ecological, resource conservation, and amenity perspectives, emphasizing that the CEIAI aims to reflect not only the absolute conservation of the environment, but also aspects of the natural environment, living environment, and human comfort. Park (2016, 2017) redefined the CEIAI as an environmental assessment index (EA-Index) and developed a system and methods for quantitatively evaluating the eco-friendliness of various types of projects, including industrial complexes, urban development projects, and road construction projects, in South Korea.

Most previous studies have qualitatively evaluated the effectiveness of EIA throughout the process or relied on subjective judgments. However, this study introduces a quantitative tool called the EA-Index to objectively measure and analyze environmental performance before and after EIA reviews. By enabling trend analysis, this study uniquely evaluates how changes in EIA policies have influenced actual environmental outcomes. This quantitative approach contributes to deriving policy implications that were not addressed in previous studies.

Most studies mentioned above evaluate the effectiveness of EIA from procedural, substantive, and transactional perspectives, as suggested by Sadler (1996), primarily through case studies. However, we focus on evaluating substantive effectiveness, specifically whether the EIA system has achieved its goals and purposes, namely, to serve as a rational decision-making process for environmental conservation. The Lee and Colley Review Package is a well-established tool for evaluating the quality and effectiveness of EIA reports. Numerous studies (Barker and Jones, 2013; Mounir, 2015; Aung et al., 2018) have used this package to provide a structured framework for assessing both the procedural and substantive effectiveness of EIA systems. By referencing this method, we aim to position our quantitative evaluation of EIA effectiveness within the broader context of established assessment methodologies.

This study evaluates the effectiveness of the EIA based on Articles 1 (purpose) and 3 (responsibilities of the state and other entities) of the Environmental Impact Assessment Act of South Korea. The evaluation focuses on whether the objectives and purposes of the system have been

achieved by examining how and to what extent the environmental impacts of the implementation of development projects have been minimized through the preparation of environmental conservation measures. This is crucial for determining how faithfully the State fulfills its responsibilities in the EIA consultation process, in line with the Act's goal of promoting sustainable development by guiding eco-friendly development.

The purpose of this study is to evaluate the effectiveness of an EIA for onshore wind power projects (WPPs) in South Korea. Specifically, it aims to analyze the effectiveness of expert reviews in the consultation process, one of the key areas of EIA, in assessing and preventing environmental impacts in advance. Additionally, this study seeks to develop a quantitative evaluation method for EIA and explore ways to minimize the environmental impacts of renewable energy (RE) projects. To achieve this, we objectively and quantitatively evaluated how plans were modified after expert reviews and how the modified plans reduced environmental impacts compared to the original plans for 112 onshore WPPs, including six rejections that completed the EIA process from 2013 to 2022. Through this process, we aim to demonstrate the substantive effectiveness of the EIA.

2. Materials and method

2.1. Effectiveness concepts and approach

The evaluation target of EIA effectiveness is defined as the review process, and individual development projects that have completed the EIA process are considered evaluation units in this study. Specifically, EIA effectiveness was assessed by calculating the EA-Index (Park, 2016) before and after the EIA review for each development project and by measuring the changes. This enables a spatiotemporal analysis of effectiveness, allowing for a detailed understanding of the impact of major environmental policy changes on decision-making in specific sectors. This concept represents an innovative approach that is both objective and simple, making it a useful tool for periodically evaluating and monitoring the effectiveness of an EIA system for various types of development projects.

Fig. 1 shows the hierarchical structure of the EA-Index along with the concept and procedure for evaluating EIA effectiveness. First, the key environmental factors, defined as the parameters primarily addressed in the EIA review process for the target projects (i.e., in this study, onshore wind power projects), should be identified and extracted, excluding any factors not included in the EIA reporting guidelines to ensure objective evaluation. Various parameters, such as air quality, ecology, and water quality, were processed to derive individual indicators. These individual indicators were then categorized based on their common characteristics to calculate the component indices that represent broader environmental domains. The EA-Index was calculated by aggregating the component indices.

For the EA-Index, a non-statistical approach was applied because the assessment requires value judgments regarding which environmental factors should be considered important based on the characteristics of the project, rather than relying on inductive reasoning from statistical analysis. The Analytic Hierarchy Process (AHP), a representative non-statistical method that systematically evaluates alternatives with different preferences for multiple evaluation criteria, was employed. This method is particularly suitable for determining the weights of individual indicators in the EA-Index because it decomposes and hierarchizes the problem in a manner similar to human thinking, allowing measurement of the relative importance of the evaluation criteria (Saaty, 1980; Ishizaka and Lusti, 2006; Vaidya and Kumar, 2006; Song et al., 2023).

Integrating multi-criteria analysis (MCA) with AHP is crucial for evaluating the effectiveness of an EIA. The MCA approach has been applied to a wide range of issues such as EIA, policy evaluations, and project assessments (Viaggi et al., 2011; Ishizaka and Nemery, 2013;

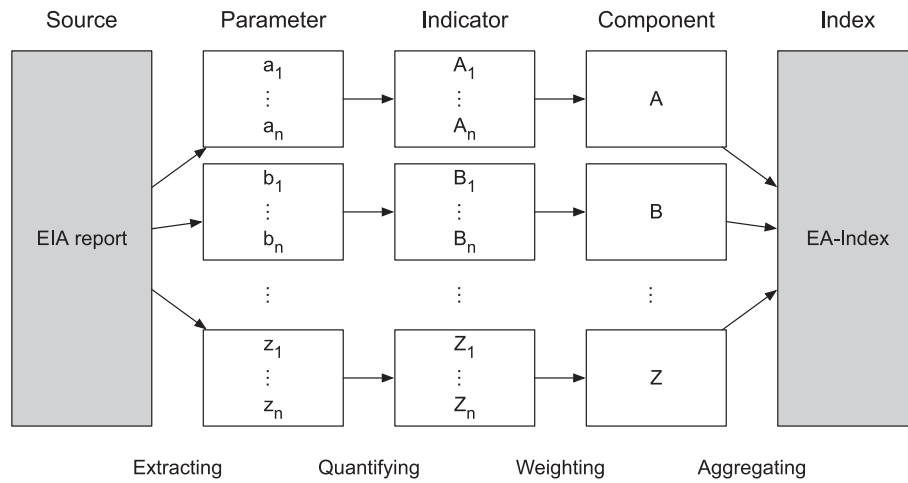


Fig. 1. Illustration of the procedure for calculating the environmental assessment index (EA-Index). The arrows pointing upwards indicate the actions to be taken at each step.

Taraszkiewicz, 2022). MCA enables the consideration of multiple environmental factors, ensuring a comprehensive assessment of the project's impact. This method offers holistic evaluation, consistent weighting, and prioritization of critical environmental factors. Therefore, the AHP method was used to assign weights to the EA-Index indicators. By structuring the decision-making process, AHP enhances the transparency and reliability of EIAs and supports the development of evidence-based environmental policies (Malczewski, 2006; Pöhlönen et al., 2018).

The calculated EA-Index was used to compare environmental conditions before and after the EIA review process to evaluate the EIA effectiveness. This involves analyzing the degree of improvement and goal achievement. Additionally, This approach is effective in identifying the key factors considered during the EIA review through spatiotemporal changes in the EA-Index as well as trend analysis of individual indicators. Furthermore, it can serve as indirect evidence to demonstrate how changes in the relevant policy environment affect decision-making.

2.2. Calculation and standardization of the environmental assessment index (EA-index)

The EA-Index was designed to quantify the quality of EIA reports by assessing various environmental parameters. The EA-Index is calculated by summing the values of the individual indicators for each sector. However, the importance of each indicator and its impact on the environmental assessment of a development project can vary depending on the project's characteristics. Therefore, it is necessary to assign weights by considering these factors.

To reflect the eco-friendliness of the development projects, the EA-Index requires the directionality of each indicator to be consistent. Therefore, for negative indicators, where higher values indicate lower eco-friendliness (e.g., forest area ratio, steep slope ratio, and pollutant emissions), a symmetric function relative to the maximum value was applied to unify directionality (Eq. (1)). The base year represents a reference value of 100 and serves as the reference point for comparison. Accordingly, it allows the measurement of the change in the indicator values relative to the reference value of 100 over the evaluation period.

$$x_{ij} = x_{ij_max} - x'_{ij} \quad (1)$$

where, x_{ij} represents the non-standardized indicator, x' represents the non-standardized negative indicator, i represents the year based on the approved date of the EIA, and j represents the type of indicator. After aligning the directionality and calculating the annual average, the indicator values were standardized relative to the base year as the

reference value (Eq. (2)). The base year served as a reference point for comparison, with its indicator value set to 100, allowing the measurement of the change in the indicator values relative to the base year over the evaluation period.

$$X_{ij} = \frac{x_{ij}}{x_{rj}} \times 100 \quad (2)$$

$$EA - Index_i = \sum X_{ij} \times Y_j \quad (3)$$

where X_{ij} represents the standardized indicator, r denotes the base year, and Y_j represents the weights for each indicator. The EA index was calculated by multiplying the standardized indicators by the weights derived through the AHP method and aggregating them (Eq. (3)).

2.3. Case study selection and description: Analyzing onshore wind power projects

The expansion of onshore wind energy in South Korea, while contributing to the country's RE goals, has raised several environmental concerns. The rapid development of wind farms has highlighted the need to effectively address these issues. In South Korea, most areas with excellent wind resources are located along mountain ridges, which naturally include valuable geomorphological and ecological corridors (Lee et al., 2017; Zhu et al., 2020). As a result, forest ecosystem degradation, geomorphology, and other environmental impacts of onshore wind power development have emerged as key issues in environmental conservation (Kwon et al., 2014). Consequently, locations or areas with excellent wind resources are not always regarded as suitable sites for onshore wind expansion (Park et al., 2021).

Moreover, the significant increase in renewable energy targets over the past decade, driven by South Korea's Renewable Energy 3020 Implementation Plan (RE3020) announced in 2017 (Ministry of Trade, Industry and Energy (MOTIE), 2017), has contributed to the rise in EIA applications for onshore wind power projects. This plan aims to increase renewable energy capacity to 20 % of the country's total energy mix by 2030. Onshore wind projects have become a key component of this strategy, but their expansion has faced challenges due to the environmental and social complexities surrounding large-scale wind farm development. Consequently, the growing emphasis on renewable energy development has led to a significant rise in EIA applications, reflecting the complexities of balancing environmental conservation with the expansion of renewable energy infrastructure.

Onshore WPPs, which cause environmental degradation, are perceived as representative cases of green-on-green conflicts, with the

consensus that they cannot be sustainable RE development models. For example, the construction and operation of onshore wind farms can lead to habitat disruption and pose risks to local wildlife. Bird and bat mortality due to wind turbine collisions has been reported, raising concerns about their impact on biodiversity (Bright et al., 2008; Kiesecker et al., 2011; Voigt et al., 2012; Peste et al., 2015). Additionally, wind turbines located near residential areas can cause visual and noise pollution. The aesthetic impact of turbines on the landscape and the noise generated by rotating blades have led to opposition from local communities, thus impacting project timelines (Pedersen and Waye, 2007; Krogh et al., 2011). However, the development of wind farms has sometimes resulted in social conflicts between developers and local communities. Issues such as land acquisition, fair compensation, and insufficient stakeholder engagement have been points of contention, highlighting the need for transparent and inclusive planning processes (Gross, 2007; Jami and Walsh, 2016).

Consequently, almost all onshore wind project developers are required to complete an EIA; however, only a few projects proceed without controversy. In response, the South Korean government is seeking ways to minimize the environmental impacts of onshore wind development projects through strategies that expand wind energy in harmony with the environment (Park et al., 2021). These measures include policy support, such as regulatory rationalization and providing EIA guidelines.

Therefore, this study selected and analyzed case studies of onshore WPPs in South Korea to evaluate the effectiveness of the EIA. First, a survey was conducted on the status of the EIAs for onshore WPPs. According to data from the Environmental Assessment Information Support System (EIASS; available at <https://www.eiass.go.kr>), 168 projects have completed the EIA between 2002 and 2022. Among these, 132 projects were approved, 8 were rejected, and 28 were withdrawn.

In terms of regional distribution, 71.2 % of the 132 projects were concentrated in the Gangwon and Gyeongbuk regions, which are located in eastern South Korea. These areas have a relatively high mountainous density, which is attributed to the spatial distribution of wind resources suitable for wind power generation. Park et al. (2021) showed that the maximum range of the capacity factor in South Korea is 34 %, and regions with a capacity factor of more than 20 % are distributed along major mountain ridges within the Gangwon and Gyeongbuk regions.

Fig. 2 shows the annual changes in the number of approved EIAs for

onshore WPPs, with a significant increase observed since 2014, although this trend decelerated between 2017 and 2019. The increase in approved EIAs after 2014 can be attributed to the revitalization of the domestic renewable energy market following the implementation of the Renewable Portfolio Standard (RPS) system in 2012, and the favorable policy environment established by the RE3020 in 2017. However, the deceleration between 2017 and 2019 can be explained by stricter environmental regulations and increasing public opposition to onshore wind projects due to environmental and social concerns as we mentioned above. During this period, a total of 28 EIA projects were submitted, of which 3 were rejected and 8 were withdrawn, resulting in an approval rate of only 61 %, compared to the overall average (2002–2022) of 79 %, indicating that EIA processes during this period were more challenging.

2.4. Defining evaluation indicators

To systematically evaluate the effectiveness of EIA for onshore WPPs, it is essential to establish a comprehensive set of evaluation indicators. These indicators were derived from key environmental considerations identified during the EIA review process to ensure a robust and quantifiable assessment of the environmental impacts.

The evaluation indicators were selected based on their relevance to environmental impacts commonly associated with onshore WPPs. Table 1 lists these key environmental considerations along with their normalized frequency of occurrence derived from expert review comments as part of the EIA process, for 55 projects obtained from the Korea Environment Institute (KEI), an institution responsible for the professional review of EIA.

Data showed that substantial attention was given to issues such as geotechnical stability (0.1349) and topographical damage (0.1217), underscoring significant considerations for ground integrity and landscape preservation. Additionally, the frequent occurrence of habitats for legally protected and endangered species (0.1151) and areas requiring ecological preservation (0.1118) reflects robust efforts to mitigate biodiversity loss. Moderate prioritization was observed for community acceptance (0.0362), monitoring plans (0.0461), and complaint management (0.0164), indicating efforts toward balanced stakeholder engagement and operational oversight. These data provided an in-depth understating of the key environmental considerations for onshore WPPs

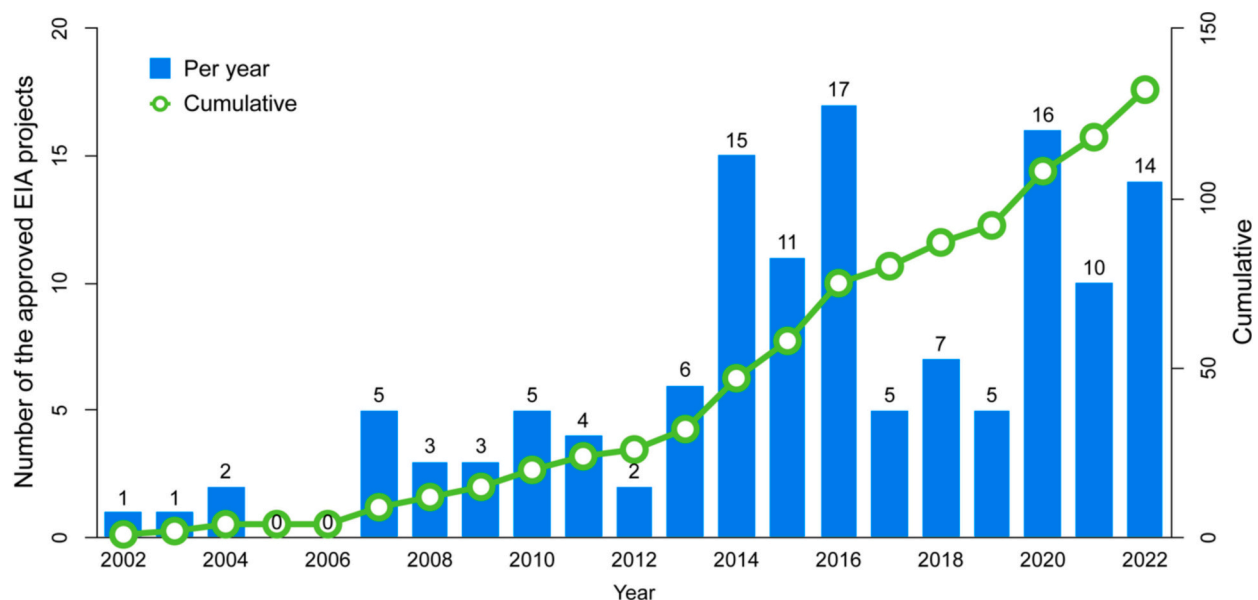


Fig. 2. Annual number of approved EIAs for onshore wind power projects in South Korea from 2002 to 2022 ($n = 132$), excluding rejections ($n = 8$) and withdrawals ($n = 28$). Projects approved in the last 10 years (2013–2022, $n = 106$) account for 80 % of the total.

Table 1

List of key environmental considerations identified in the EIA review process for onshore wind power projects.

Environmental considerations	Frequency ^a
<i>Biological environment</i>	
a1. Natural ecological areas that need to be preserved	0.112
a2. Important vegetation areas, and a3. forest land	0.049
a4. Habitats for legally protected and endangered species	0.115
a5. Bird mitigation measures	0.039
<i>Geology and topography</i>	
b1. Geotechnical stability (e.g., steep slope of above 20 degree)	0.135
b2. Topographical damage (e.g., cut-and-fill), and b3. construction of an access road	0.122
b4. The ridgeline of the mountain, well-preserved in its natural state and connectivity	0.095
<i>Land use and landscape</i>	
c1. Environmentally sensitive areas (e.g., national parks, natural habitats)	0.013
c2. Damage to the natural and mountain landscapes	0.020
<i>Hydrology and water quality</i>	
d1. Drainage network and hydrogeology (e.g., mountain valley)	0.007
d2. Soil loss and d3. surface water quality (e.g., BOD)	0.086
<i>Resource recycling</i>	
e1. Processing of felled trees	0.020
<i>Noise and vibration</i>	
f1. Distance from residential areas, and f2. low-frequency noise mitigation	0.076
f3. Low-frequency noise monitoring plan	0.046
<i>Air quality</i>	
g1. PM ₁₀ and g2. NO ₂ from construction dust	0.013
<i>Social environment</i>	
h1. Community acceptance	0.036
h2. Complaint management measures during operation	0.016

Note: The labels (e.g., a1 and b1) are assigned to each environmental consideration to match them with the corresponding parameters in the EA-Index.

Note: Italic words indicate the environmental components being addressed in the EIA.

^a Calculation of the normalized frequency for each consideration as a keyword: frequency of the keyword / total frequency sum (304 occurrences).

in South Korea.

Based on these key environmental considerations, 23 parameters of the EA-Index that could be extracted from the EIA report were derived. Two parameters—greenhouse gas reduction (s1) and carbon sink (s2)—were added to consider the environmental benefits of RE in the context of climate change adaptation. Table 2 presents the framework of the EA-Index components for onshore WPPs, including the evaluation criteria, corresponding parameters, and quantification methods for the EA-Index indicators.

The weights for each indicator were derived using the AHP, reflecting their relative importance in the overall assessment. The AHP weighting was determined with the participation of 31 experts from stakeholder groups related to onshore wind power to ensure the validity of the indicator selection and objectivity of the weighting results (Table 2). The results indicate that the natural environment component holds the highest importance, with a weight of 0.44, emphasizing the priority of ecological conservation and minimizing topographical damage. Resource conservation had a weight of 0.32, highlighting the importance of climate change mitigation. Living and social environments had a weight of 0.24, reflecting the significance of noise and community acceptance. This outcome reflects the importance of ecological protection and the balanced consideration of various environmental factors in sustainable development.

The quantification of each parameter involves different methods such as numerical value application (Quant) and presence/absence or inclusion/exclusion investigation (Y/N) using binary representation. For instance, parameters such as habitats for legally protected species (a4) were evaluated based on their presence or absence at the project site. Parameters related to air quality (g1 and g2) were quantified numerically based on the mitigation measures in place.

Table 2

Framework of the EA-Index components for onshore wind power projects and evaluation criteria by indicator. Values in parentheses indicate the composite weights obtained from the AHP method for each indicator and component.

Indicator group	Evaluation criteria	Parameter ^a	Method ^b
Natural environment (0.44)			
Ecology (0.27)	Has the project site avoided well-conserved ecological areas?	a1, a2, a3	Quant
	Has a habitat conservation or restoration plan been established?	a4, a5	Y/N
Topography (0.09)	Has the plan been designed to minimize topographical change or damage?	b1, b2, b3	Quant
	Has the development avoided damaging major mountain ridges?	b4	Y/N
Landscape (0.09)	Has the project site avoided landscape sensitive areas?	c1	Y/N
	Has the plan to mitigate landscape impacts been established?	c2	Y/N
Resource conservation (0.32)			
Water resource (0.08)	Has the plan been designed to minimize water quality impacts during construction?	d2, d3	Quant
	How much greenhouse gas reduction is expected due to the production of renewable energy?	s1	Quant
Climate change ^c (0.18)	Is there no damage to carbon sinks?	s2	Quant
	Has the plan been established for the disposal of tree waste generated by the development?	e1	Y/N
Recycling (0.06)			
Living and social environment (0.24)			
Noise (0.08)	Are the site selection and measures for minimizing the impact of low-frequency noise appropriate?	f1, f2, f3	Quant
	Has the plan been designed to minimize air pollutant emissions during construction?	g1, g2	Quant
Community (0.11)	Has a plan been established to ensure community acceptance?	h1, h2	Y/N

Note: Italic words indicate components of the EA-Index.

^a Parameters represent the environmental considerations listed in Table 1, except s1 and s2.

^b Quantification method for the parameter (e.g., a1 to A1 as shown in Fig. 1): numerical value application (Quant), presence/absence or inclusion/exclusion investigation (Y/N) using binary representation (0 or 1). A value of 1 indicates presence or inclusion, while a value of 0 indicates absence or exclusion.

^c Additional parameters for climate change adaptation aspects: s1 and s2.

The EA-Index is calculated by summing the weighted values of these indicators, providing a comprehensive score that reflects the overall environmental quality of the project based on EIA report.

EIA reports were collected from the EIASS, which served as the data source for the EA-Index inputs. We used 188 EIA reports from 109 projects that completed the EIA process during the evaluation period (2013–2022). This includes 158 reports from 79 projects that received approval with supplementary conditions, which means that both the initial version of the reports submitted for the EIA review and the final version of the reports were revised after additional review (pre- and post-approval, respectively). Additionally, 24 projects that received approval without supplementary conditions, excluding three non-disclosed reports and six rejected projects, were included.

3. Results and discussion

3.1. Temporal changes in EA-index

Between 2013 and 2022, 106 projects, accounting for 80 % of the total, received EIA approval. The evaluation of EIA effectiveness focused

on this period, during which the cumulative project area reached 13.7 million m², with an average of 107,000 m² per project. About 37 % of the total projects were within 50,000–100,000 m². The cumulative installed capacity was 3.6 GW, averaging 30.8 MW per project. Fig. 3 shows the increase in average turbine capacity from 1.9 MW in 2013 to 4.7 MW in 2022, a 2.5-fold growth over a decade. Enhancing turbine capacity demonstrates improved land-use efficiency, reducing the land required for development projects. For instance, a 32.4 MW wind farm with 10 turbines of 3.2 MW capacity each would require approximately 120,000 m² of land, providing insight into the scale of recent onshore WPPs subjected to EIAs in South Korea.

This section discusses the temporal changes observed in the EA-Index before and after approval over the ten-year evaluation period (2013–2022). This analysis provides a comprehensive understanding of how the EA-Index has evolved over time and the factors contributing to these changes. In particular, the analysis compared changes in the EA-Index before and after approval to assess the effectiveness of the review process. This approach assumes that the EA-Index of the improved project plans revised after an additional review (post-approval) will always be higher than the initially submitted plans before the review (pre-approval). The base year for calculating the EA-Index was 2013, the first year of the evaluation period, with the pre-approval average EA-Index set to a reference value of 100.

Fig. 4 shows the distribution of the EA-Index pre- and post-approval for 79 onshore WPPs by the year of EIA approval. The data reveal that the average EA-Index index generally increases over time, indicating improvements in environmental performance through the EIA process. However, there were fluctuations, with some years showing more significant improvements than others.

Increases in the EA-Index post-approval compared to pre-approval showed a tendency to exceed the reference value of 100 more significantly over time. Notably, the increase was relatively large from 2017 to 2020, with an average increase of 19.5. This indicated that the demand for environmental improvements during the review process was relatively high at different times.

The results also indicated that the variance of the EA-Index post-approval was relatively higher than that pre-approval. The minimum and maximum EA-Index values were 62.5 (in 2014, pre-approval) and 164.5 (in 2020, post-approval), respectively, with most projects ranging from 80 to 140.

Fig. 5 compares the average EA-Index and its components (natural environment, resource conservation, and living and social environments) before and after the approval over the entire evaluation period. The analysis showed that all components improved after approval, with

the natural environment component exhibiting the most significant increase at 25.9 %. Consequently, the average EA-Index increased by approximately 12 %, from 105.4 pre-approval to 117.9 post-approval. The resource conservation, living, and social environment components also showed environmental improvements of 2.6 % and 5.6 %, respectively, throughout the review process, although these increases were not significant.

The results highlighted the importance of indicators in the natural environmental component of the EIA review process for onshore WPPs. This is reflected in the AHP weighting, which assigns the highest proportion of 44 %, as shown in Table 2, and the relatively high-level evaluation criteria related to site selection (i.e., ecology, topography, and landscape).

3.2. Evaluation of the EA-index by EIA decision

The EA-Index was evaluated by categorizing onshore WPPs based on their EIA decisions during the evaluation period. It assessed whether the EA-Index effectively reflected the differences in eco-friendliness among projects with varying EIA outcomes. This analysis provides insights into the extent to which the EIA process distinguishes projects with different environmental performance levels.

Onshore WPPs were categorized into three groups based on their EIA decisions: approved without supplementary conditions ($n = 24$), approved with supplementary conditions ($n = 79$), and rejected ($n = 6$). The EA-Index values for each category were compared to identify any significant differences that highlight the ability of the EIA process to discriminate between environmentally sound and unsound projects. Here, we expected that the EA-Index of rejected projects is generally lower than that of approved projects, and the EA-Index of projects approved without supplementary conditions is higher than that of projects approved with supplementary conditions before the review (pre-approval).

Table 3 summarizes the results of the average EA-Index evaluation by component (natural environment, resource conservation, and living and social environment) and its success rates for 109 onshore WPPs based on decisions on EIA report approvals from 2013 to 2022. A reference value of 100 was set as the target, and projects with an EA-Index above 100 were considered successful. The data show that projects approved with supplementary conditions post-approval had the highest average EA-Index (117.9), indicating the most significant environmental improvements after the review. Projects approved without supplementary conditions had an average EA-Index of 111.8, reflecting strong environmental performance without the need for additional

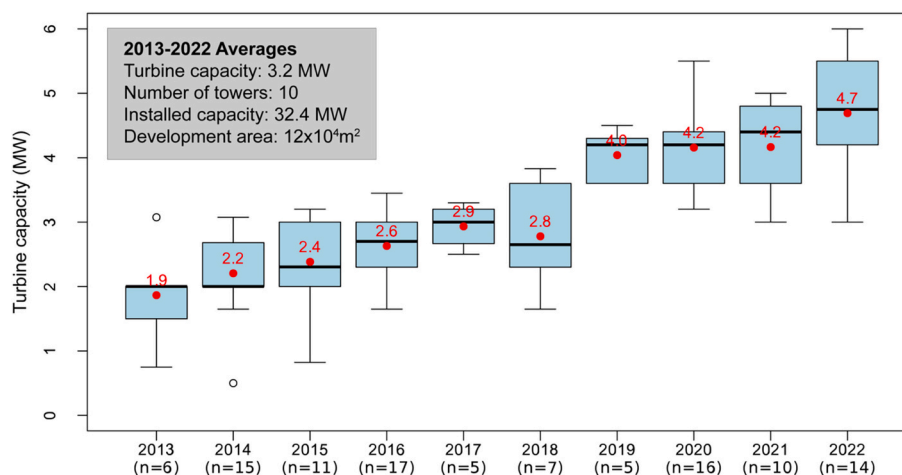


Fig. 3. Box-and-whisker plots showing the annual changes in onshore wind turbine capacity by year of EIA approval (2013–2022, $n = 106$). The red dot in each box indicates the average turbine capacity for that year. The box in the top left summarizes the average values for the 2013–2022 period, indicating the average scale of the projects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

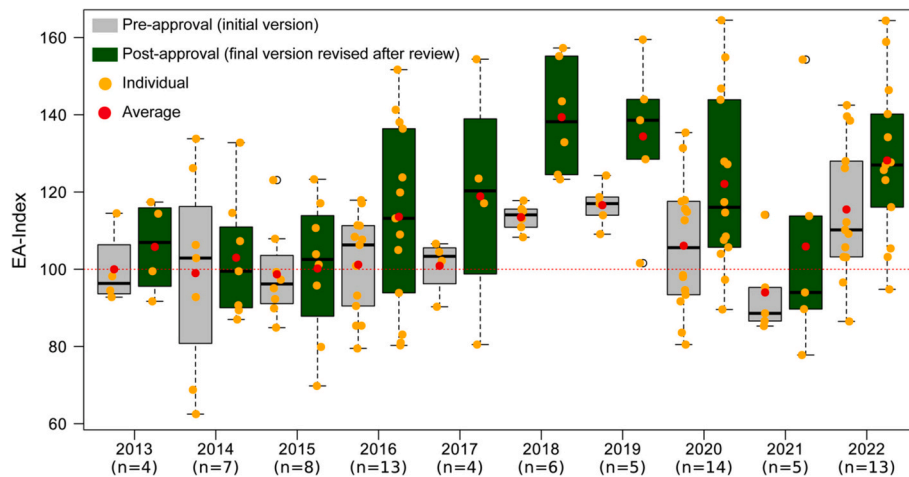


Fig. 4. Distribution of the EA-Index pre- and post-approval for onshore wind power projects ($n = 79$) by year of EIA approval (2013–2022). The red dashed horizontal line indicates the reference value of 100. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

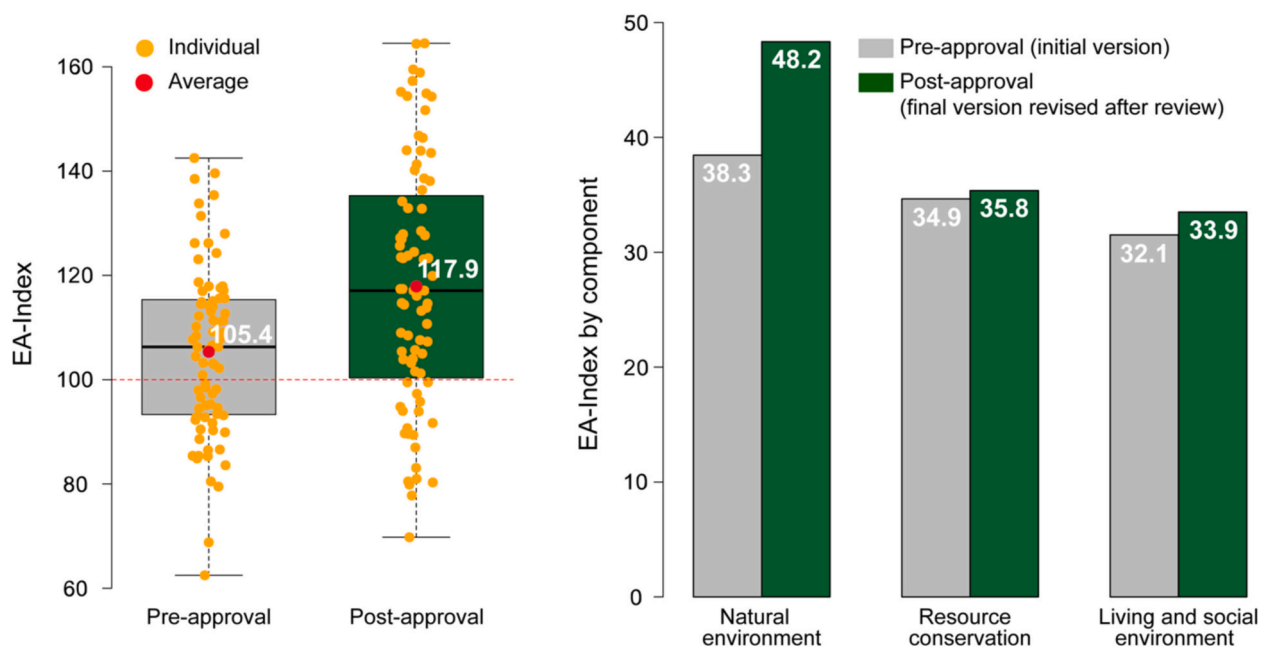


Fig. 5. Comparison of average (2013–2022) EA-Index by component-based analysis in individual onshore wind power projects ($n = 79$) from pre- and post-approval. Boxplots (left) show the distribution of improvements in environmental conservation plans of the projects during the EIA review process. Barplots (right) show the average value for each component, indicating that the sum of these three components equals the EA-Index.

Table 3

Evaluation of the EA-Index and its success rates (projects with an EA-Index above the reference value are considered successful) for wind power projects based on the decision on EIA report approval from 2013 to 2022.

Decision on EIA report approval		No. of projects	Average EA-Index by component				Proportion exceeding the reference value of 100
			NE (A)	RC (B)	LS (C)	EA-Index (A) + (B) + (C)	
Rejection		6	34.4	28.3	34.9	97.6	50.0 %
Approval with a supplementary condition ^a	Pre	79	38.3	34.9	32.1	105.4	60.8 %
	Post	79	48.2	35.8	33.9	117.9	74.7 %
Approval without a supplementary condition ^b		24	41.4	38.0	32.5	111.8	79.2 %

Note: three components of the EIA-Index are natural environment (NE), resource conservation (RC) and living and social environment (LS).

^a The EIA report was found unsatisfactory during the review process, which means that a revised EIA report is required for additional review before approval.

^b Out of a total of 27 projects, three were excluded from the EA-Index calculation due to the non-disclosure of their EIA reports.

revisions. The rejected projects had the lowest EA-Index values (97.6), underscoring their relative environmental inadequacy.

In particular, rejected projects show a significantly lower value for the natural environment component than other approved projects. This suggests that the rejected projects were located in environmentally sensitive areas or had a substantial impact on the ecosystem, which has not been adequately addressed in terms of natural environment conservation. The value of the resource conservation component was also low, indicating insufficient mitigation measures and protection plans. While the value of the living and social environment components was relatively low, it did not show a significant difference from other approved projects. Ultimately, the rejected projects were notably lacking in terms of natural environment and resource conservation, which appear to be major factors contributing to their rejection during the EIA review process. These characteristics not only illustrate how the evaluation indicators impact project approval decisions but also support the assumption mentioned earlier.

The success rates calculated using the proportion of projects exceeding the reference value of 100 also support these findings: 79.2 % for projects approved without supplementary conditions, 74.7 % for projects approved with supplementary conditions (post-approval), and 50.0 % for rejected projects. These results highlight the robustness of the EA-Index as a tool for evaluating the environmental quality of onshore WPPs.

3.3. Analysis by environmental sensitivity

To categorize the onshore WPPs based on their site characteristics, a cluster analysis by *k*-means algorithm was performed using the R package “cluster”. This analysis aimed to identify distinct clusters that reflect the varying degrees of environmental sensitivity of the sites and assess the EA-Index for each cluster to determine how well the EA-Index captures differences in eco-friendliness.

The input data for the clustering analysis included key site evaluation indicators in the natural environment component, such as the proportion of forestland (same as parameter a3 in Table 1), important vegetation cover classified as high conservation value (parameter a2), and slope steepness (parameter b1). These areas were identified as environmentally sensitive when they had a high proportion, and it was assumed that they would have a relatively lower EA-Index than the less sensitive areas. The 188 cases of the 109 projects for the evaluation period (2013–2022) were grouped into four distinct clusters based on these three indicators. Table 4 summarizes the results of the cluster analysis, including the average EA-Index and ANOVA test statistics for each cluster.

The results showed that the EA-Index by cluster reveals significant

differences in environmental performance among the clusters as follows: Cluster 1 ($n = 56$), characterized by high forest and vegetation cover combined with steep slopes, has the lowest average EA-Index of 93.6. This low value suggests that projects in Cluster 1 face greater environmental challenges and potential impacts owing to their sensitive locations. High forest and vegetation cover, along with steep slopes, indicate that these areas are more vulnerable to environmental disturbances, leading to a lower EA-Index, indicating Cluster 1 as the most sensitive area.

In contrast, Cluster 2 ($n = 60$), which also had high forest and vegetation cover but mostly gentle slopes, had a higher average EA-Index of 104.0. The gentle slopes in these areas caused less topographical change or damage than the steep areas in Cluster 1, resulting in a higher EA-Index.

Cluster 3 ($n = 41$) presents a different scenario. Although it has a high proportion of forest land, the vegetation cover is relatively low, and the slopes are relatively steep. Despite steep slopes, the average EA-Index of this cluster was 114.0. Lower vegetation cover might mitigate some of the environmental impacts typically associated with steep slopes, resulting in a relatively higher EA-Index compared to Clusters 1 and 2. Finally, Cluster 4 ($n = 31$), which features low proportions of both forest and vegetation cover and few steep slopes, had the highest average EA-Index of 120.0. This indicates that the projects in Cluster 4 had the lowest environmental sensitivity compared to the other clusters. The low presence of forest and vegetation, combined with gentle slopes, suggests that these areas are less prone to significant environmental impacts, leading to the highest EA-Index among the clusters.

The results indicate that the differences in the EA-Index among the clusters were statistically significant ($p < 0.001$), highlighting the robustness of the EA-Index in reflecting environmental sensitivity based on site characteristics (Table 4). Therefore, these results not only demonstrate how the site of onshore WPPs impacts the EA-Index based on environmental sensitivity but also support our earlier assumptions. This suggests that the development sites in Cluster 1 require a more careful and thorough evaluation during the EIA review process than those in Cluster 4 and the others. This analysis underscores the importance of incorporating environmental sensitivity into the EIA review, highlighting that the EA-Index effectively captures the differences in eco-friendliness based on site characteristics.

4. Policy implication

The policy implications derived from the EA-Index analysis of onshore WPPs over the evaluation period (2013–2022) are discussed in terms of the EIA effectiveness. Figs. 6 and 7 provide insights into the effectiveness of policies and their impact on environmental

Table 4

Analysis of the average EA-Index for onshore wind power projects based on the proportion of environmentally sensitive areas by cluster: ANOVA results. 188 cases were applied for calculating the EA-Index.

	Proportion of area (%) ^a			Average EA-Index (standard deviation)		ANOVA test ^b	
	Forest	Vegetation	Steep slope			<i>F</i>	Sig.
Cluster 1 ($n = 56$)	96.8	77.4	54.5	93.6	(20.6)	20.6	0.000***
Cluster 2 ($n = 60$)	90.6	72.1	8.9	104.0	(21.1)	12.8	0.000***
Cluster 3 ($n = 41$)	93.1	13.1	30.9	114.0	(21.0)	10.0	0.000***
Cluster 4 ($n = 31$)	14.5	11.3	15.2	120.0	(22.0)	15.2	0.000***

Note: Cluster 1: areas with very high proportions of forest and vegetation, and steep slopes. Cluster 2: areas with high proportions of forest and vegetation, and mostly gentle slopes. Cluster 3: areas with a high proportion of forest land but low vegetation, and relatively steep slopes Cluster 4: areas with low proportions of forest and vegetation, few steep slopes.

^a Forest (parameter a3) refers to land classified as forest in terms of land category. Vegetation (parameter a2) refers to ecologically important vegetation areas classified as high conservation value. Steep slope (parameter b1) refers to areas with a slope above 20 degrees.

^b df between groups = 3 and df within groups = 184.

*** $P < 0.001$.

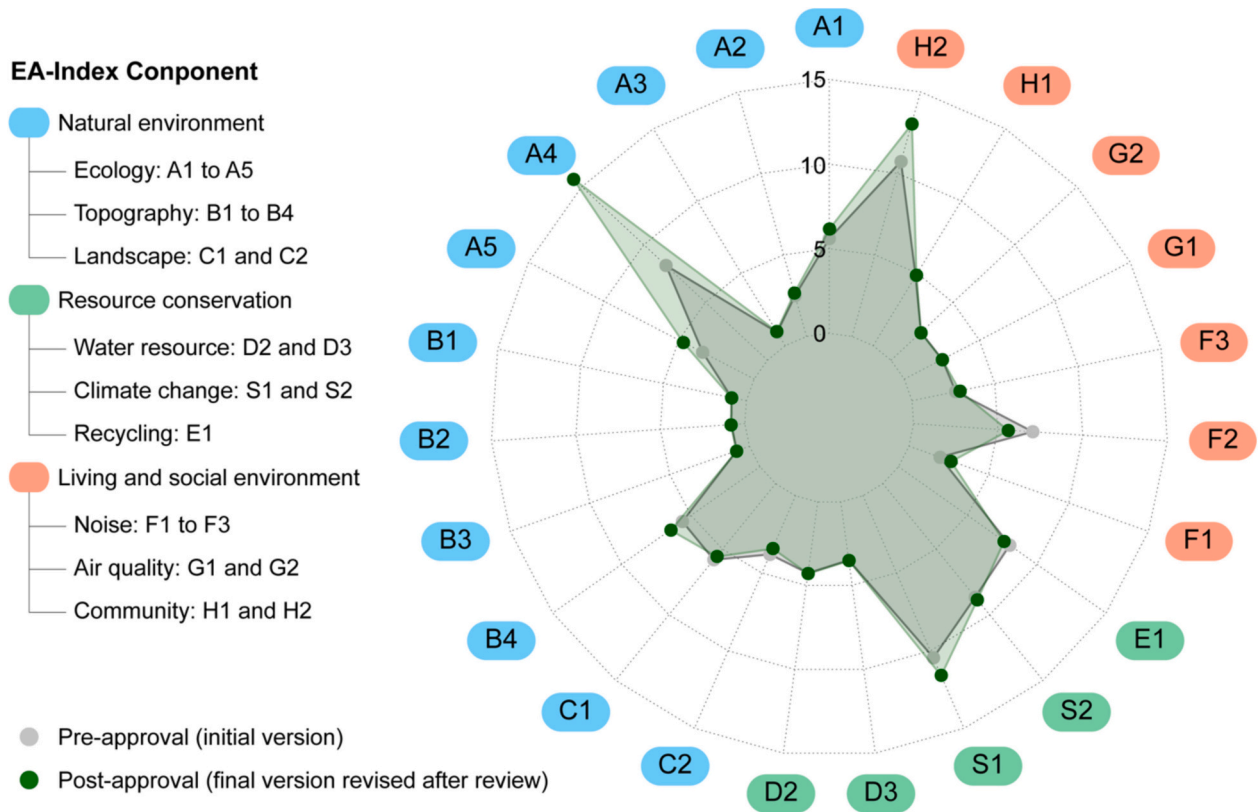


Fig. 6. Radar chart showing the average (2013–2022) EA-Index results based on the analysis of 23 individual indicators in three components for onshore wind power projects ($n = 79$) from pre- and post-approval. Letters in the rounded rectangles represent the indicators quantified from the parameters listed in Tables 1 and 2.

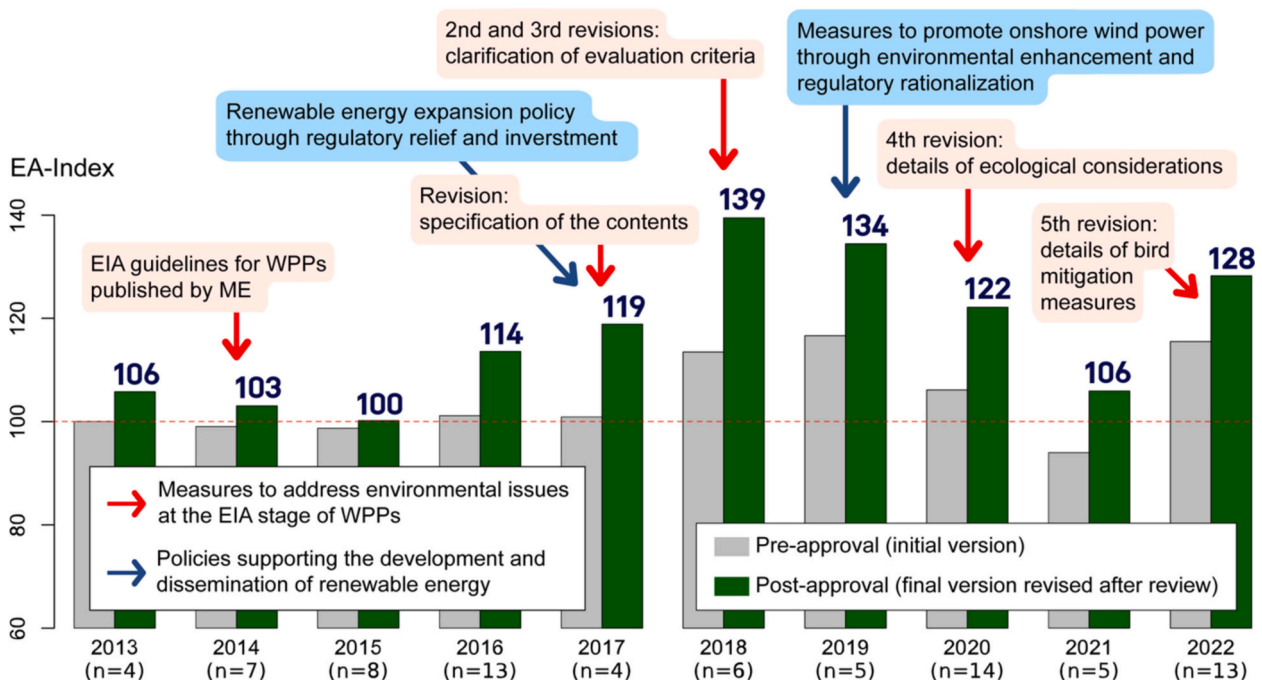


Fig. 7. Trend analysis of the annual average EA-Index for onshore wind power projects (WPPs) pre- and post-approval over the last 10 years (2013–2022, $n = 79$), showing the relationship between policy and decision-making for EIA. Red and blue arrows indicate the years when policies were announced by the Korea Ministry of Environment (ME) or the government. The red dashed horizontal line indicates the reference value of 100. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

performance, as measured by the EA-Index.

The radar chart in Fig. 6 shows the average EA-Index results based on individual indicators across the three components (natural environment, resource conservation, and living and social environments) for the 79 onshore WPPs before and after approval. The EA-Index post-approval of the 23 indicators in the three components generally showed higher values, indicating improved environmental performance after the EIA review. Specifically, certain indicators in the natural environment component increased significantly: habitat conservation (A4) increased by 7.5, followed by bird mitigation measures (A5) by +1.3, mountain ridge preservation (B4) by +0.8, and ecological area conservation (A1) by +0.6. Additionally, the results show an increase of 2.3 in the community acceptance indicator (H2) for the living and social environment components. The significant increase in the H2 indicator reflects growing efforts to actively involve local communities in the decision-making process for onshore wind power projects. Engaging stakeholders from the early stages of the EIA process is crucial for preventing potential environmental and social conflicts. By establishing consultative bodies, holding public hearings and workshops, and ensuring transparent communication, stakeholder concerns can be addressed, leading to a more inclusive and effective EIA process. This approach not only strengthens the legitimacy of decision-making but also reduces the likelihood of social conflicts, resulting in better outcomes for both the environment and local communities (Jami and Walsh, 2014; Guan and Zepp, 2020; Kim and Lee, 2021). These findings indicate the increasing emphasis on community acceptance throughout the EIA review process. However, there were slight decreases within a range of -1.5 to -0.3 in four indicators: low-frequency noise mitigation (F2), the disposal of tree waste (E1), landscape impacts mitigation (C2), and landscape sensitive areas (C1).

Since 2018, significant emphasis has been placed on certain indicators of the natural environment. This emphasis resulted from the revisions of the EIA guidelines for WPPs by the Korea Ministry of Environment in 2017 and 2018, which clarified the related evaluation criteria. Consequently, the average EA-Index pre- and post-approval in 2018 increased from 113.5 to 139.5, representing an increase of 26.0, which was the largest increase observed during the evaluation period. This demonstrates how policy impacts EIA decision-making and quantifies its effectiveness through the distribution of the EA-Index using specific indicators, that is, factor analysis. Additionally, it demonstrates the potential of this approach as a tool for providing critical feedback for policy improvement.

Fig. 7 presents a trend analysis of the annual average EA-Index for onshore WPPs pre- and post-approval during the evaluation period as well as the relationship between policy and decision-making for EIA. The analysis clearly shows that government policy measures supporting the development and expansion of RE have had a positive impact on EIA decision-making, as evidenced by the trends in the EA-Index.

The EIA guidelines for onshore WPPs were drafted in 2014 to assist developers and regulators with project planning, approval, and implementation. These guidelines aim to contribute to the policy of expanding RE by preserving excellent natural environments and minimizing the environmental impacts of development through the EIA system. Nevertheless, during the period from 2013 to 2017, while the annual average EA-Index pre-approval showed no significant change from the reference value of 100, the increase in the EA-Index post-approval was more pronounced (Fig. 7). Thus, the effect of these guidelines on policy implementation seems to be more significant during the review process than as a preventive measure. This could mean that developers perceive these environmental strengthening measures as regulatory provisions that may create difficulties in advancing their projects.

In 2017, the government announced a policy to expand RE, including regulatory relief in site selection and increased facility investment, to achieve deployment targets by 2030. However, because onshore wind power deployment fell significantly short of its target, the government announced measures to promote onshore wind power in 2019. The

inclusion and specification of regulatory site-related factors in the revised EIA guidelines facilitated the advancement of onshore WPPs. This led to a slight decreasing trend in the EA-Index post-approval, owing to the relaxation and clarification of the evaluation criteria for ecologically sensitive areas.

Evaluating the effectiveness of EIA using the EA-Index provides critical policy implications. The EA-Index serves as a quantitative tool for measuring and analyzing the impact of policy changes on environmental performance. By tracking changes in the EA-Index, policymakers or decision-makers can identify which aspects of the EIA guidelines are most effective in enhancing environmental outcomes and which areas require further improvement. This feedback loop allows for the continuous refinement of EIA policies, ensuring that the development of onshore WPPs aligns with environmental conservation goals. Moreover, the EA-Index can help balance the need for RE expansion with the imperative to protect the natural and social environments, ultimately contributing to more sustainable development practices. While previous studies by Yoo et al. (2010, 2011) and Park (2016, 2017) laid the groundwork for developing and applying the EA-Index by focusing on its principles and quantitative evaluation methods across various project types, this study advances the field by applying the EA-Index to evaluate the effectiveness of EIA specifically for onshore WPPs. Unlike earlier studies that centered on the index's development, this study demonstrates its practical utility in tracking policy-driven changes in environmental performance and identifying actionable areas for improvement.

Even though some onshore WPPs have received EIA approval, they continue to face environmental and social conflicts. These conflicts arise from the complex and evolving nature of environmental impacts, which may not be fully addressed during the EIA process. Additionally, concerns about biodiversity, noise, and visual impacts, and the perception of insufficient stakeholder engagement are often cited as major contributors to social conflicts (Warren and Birnie, 2009; Lee et al., 2017; Lee and Park, 2021). Therefore, ongoing monitoring, adaptive management, and institutional improvements to ensure sustained stakeholder engagement throughout the entire project lifecycle are necessary. These measures are essential for mitigating conflicts and ensuring the long-term success of the project.

This study emphasizes the importance of adjusting the environmental assessment process to fit the specific regulatory frameworks and environmental conditions of each region. For instance, when certain indicators show a continuous decline or minimal improvement despite strict regulations, environmental impact assessments must play a crucial role as a decision-making tool. This can ultimately be understood as a virtuous cycle that enhances the environmental sustainability of development projects through institutional improvements. Therefore, the findings of this study provide insights into how the EIA process can be adapted in other national contexts, enabling the effective evaluation of environmental performance despite differences in policies and societal priorities.

5. Conclusions

The effectiveness of the Environmental Impact Assessment (EIA) for onshore wind power projects (WPPs, $n = 79$) in South Korea over the last 10 years (2013–2022) was evaluated using the Environmental Assessment Index (EA-Index) based on multi-criteria analysis. This study assesses how well the EIA review process mitigates environmental impacts and supports the development goals. The EA Index provides a structured and objective method for measuring the effectiveness of an EIA.

Results showed a general improvement in environmental performance after the EIA review, with the average EA-Index increasing from 105.4 pre-approval to 117.9 post-approval. Success rates exceeding the reference value of 100 rose from 60.8 % to 74.4 %. The significant increase from 2017 to 2020 reflects the impact of the revised EIA guidelines and stricter criteria, suggesting that the EIA review process

effectively identified and mitigated the potential environmental impacts.

However, these improvements may also have been influenced by enhanced environmental protection policies or advancements in related technologies. Conversely, a decrease in the EA-Index indicates declining eco-friendliness and limited EIA effectiveness, owing to lower criteria or concentrations in sensitive areas. Large variances suggest potential issues with predictability and consistency, whereas smaller variances indicate more consistent performance and predictability.

Projects approved under the supplementary conditions had the highest EA-Index, indicating substantial environmental improvements. Projects approved without supplementary conditions also initially performed well. Rejected projects had the lowest EA-Index values, highlighting inadequate environmental considerations. To enhance EIA effectiveness, it should be verified that the EA-Index for approved projects remains higher than that for rejected projects. For projects approved without supplementary conditions, the EA-Index should ideally be higher than the pre-approval values.

The variation in the EA-Index across different clusters indicated significant site-specific influences. Therefore, the EIA guidelines should be tailored to address these unique characteristics more effectively. The distinct differences in the EA-Index values support its robustness as a tool for evaluating environmental quality.

Policy measures that positively affect the EA-Index highlight the importance of supportive regulatory frameworks and targeted interventions. The continued refinement of EIA guidelines, increased stakeholder engagement, and transparent decision-making can further enhance EIA effectiveness.

Based on the evaluation results of the EIA effectiveness for onshore WPPs in South Korea using the EA-Index, the following recommendations are made:

1. Continuously refine EIA policies to address emerging environmental issues while promoting sustainable development.
2. Implement stringent evaluations for projects in environmentally sensitive areas.
3. Enhance stakeholder engagement to resolve social conflicts and improve community acceptance.
4. Develop comprehensive EIA guidelines and provide reasonable evaluation criteria for both developers and regulators.
5. Institutionalize the EA-Index as a standard tool for evaluating the effectiveness of an EIA across various types of development projects.

Although the EA-Index is valuable for measuring environmental performance, it requires extensive data and does not consider all impacts. In particular, fully assessing environmental impacts through a single quantitative indicator can be challenging, and ensuring that the measured performance translates into actual environmental improvements remains difficult. For example, even if the indicators for resource conservation and the living and social environment show high values, they only account for the presence of mitigation measures without evaluating their effectiveness.

Moreover, while the EA-Index provides a robust framework for evaluating environmental performance in South Korea, its application to other countries would require methodological adaptations. The weighting of indicators and criteria used in the EA-Index is tailored to South Korea's specific regulatory, environmental, and social contexts. Future research should recalibrate the weightings and revise criteria to reflect local conditions and regulatory environments, thereby validating the EA-Index's robustness in different national contexts.

In addition, the applicability of the EA-Index to different types of projects, such as solar power and road construction, should be explored to further validate its versatility. Given that environmental policies, legal frameworks, and societal priorities vary significantly across nations, future studies should assess the adaptability of the EA-Index to better understand its global applicability and ensure its effectiveness

across diverse regulatory environments.

In conclusion, this study demonstrated the effectiveness of South Korea's EIA system for onshore WPPs, showing significant improvements in environmental performance post-review. The EA-Index is a valuable tool for assessing EIA effectiveness and providing critical policy implications and recommendations for enhancing environmental conservation and sustainable development.

CRedit authorship contribution statement

Jong-Yoon Park: Conceptualization, Visualization, Writing – review & editing. **Ji-Hyeon Park:** Investigation, Data curation, Formal analysis. **Hyun-Jin Choi:** Methodology, Validation.

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.

Acknowledgements

This paper is based on the results of the research work “A Study on the Effectiveness Evaluation of Environmental Impact Assessment for Renewable Energy Projects (2022-122)”, conducted by the Korea Environment Institute (KEI) upon the request of the Korea Ministry of Environment. It was also supported by the research project, “A Review for Strategic Environmental Assessment (RE2024-07)”, funded by KEI.

Data availability

The authors do not have permission to share data.

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