Multi-scale landscape visual impact assessment for onshore wind farms in rural area of China

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Abstract

Growing attention on global de-carbonization, energy security, and sustainable development has made wind energy one of the most popular renewable energy sources. With the trend of huge-size wind turbines and more distributed wind farms constructed in densely populated areas of China, the impact of wind turbines on landscape can't be ignored. This paper aims to assess landscape visual impact at different spatial scales caused by large-size wind turbines. Several wind farms with different topographic and spatial scales in the Yangtze River Delta of China were selected for viewshed analysis in GIS. Based on the theoretical research on visual perception mechanism and visual impact threshold, the indicators are collected by questionnaires and analyzed with linear regression analysis. The outcomes imply that dynamic components are highly related indicators within a close distance (< 1 km), landscape aesthetics are correlated within a middle distance (1-4 km), and ecological elements are significant at a large distance (> 4km). This paper explores correlated indicators of visual impact at different spatial scales that provide recommendations for wind farm site selection.

Keywords: Wind farm; landscape visual impact assessment; GIS; visual impact threshold

I. INTRODUCTION

The global demand for renewable energy is growing under the impact of climate change. Wind energy is one of the effective solutions to achieving the carbon-neutrality target for various countries. By 2021, over 100 countries have chosen wind energy as the substitute for fossil fuels. Based on the Global Wind Report, the cumulative capacity of wind energy has reached 837GW at the end of 2021 [1]. Among them, onshore wind is the mainstream with a 93% share. Onshore wind is favorable with comparatively low prices, mature technologies, and a broad market. However, the rapid expansion of wind facilities encountered various disturbances, including environmental, socio-cultural, political, economic, and community dimensions [2][3][4].

China ranks first as the leading country in both cumulative wind energy capacity and annual installation. Although the wind industry in China started later than in western countries, it currently occupies a large proportion of the global wind market in the last decade. By 2021, the total wind capacity achieved 338 GW, accounting for around 40% of the world [5]. The dramatic growth of wind capacity concentrates in the north and west provinces, causing the unbalancing spatial distribution of wind farms and serious wind curtailment [6][7]. As the annual yield of wind energy increases, the unbalanced spatial distribution of the supply side and the consumption side imposes a great burden on the grid connection of wind power and long-distance high-voltage transportation.

According to the 14th Five-Year Plan, low-speed, distributed wind farms are encouraged to be built in densely populated areas in southeast China to release burdens on grid connection and electricity transition [8]. The policy mitigates regional disparities, but it aggravates land-use conflicts and environmental impact in the locality, which causes fierce community resistance and puts challenges to spatial planning and wind project operation [9].

II. VISUAL IMPACT

The environmental impacts caused by wind energy are much fewer than by conventional energies. However, the installation of large-scale wind farms has gradually generated the conflicts between environment and wind energy development [10][11]. The landscape visual impact receives universal public attention as the number and height of WTs grow. Because it brings broad influences to people's daily life in an extensive spatial area. For areas with traditional and rural landscapes, the visual pollution is recognized as an impairment of local identity, and disturbing landscape aesthetics [12][13]. The extremely huge vertical scale of the wind turbines creates a huge contrast with the elements of the natural landscape. For a 20 to 25-year operation period, the

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visual impact and landscape degradation are considered an irreversible threat to the place identity.

As wind energy pioneers, Germany, the United Kingdom, and other European countries have developed various approaches to landscape visual impact assessment in wind farm planning.

Gerhards discusses the existing methods and classifies them into two paradigms: objective paradigm (or expert paradigm/spatial paradigm) and subjective paradigm (or psychophysical paradigm) according to whether the evaluators influence the evaluation results or not (Table 1) [14]. The objective methods are mainly developed by Nohl [15][16], Köppel et al. [17], Gerhards [14], and Roth [18][19], which advocate expert participation, standardized evaluation process, and quantitative analysis free from any influence from landscape viewers. The subjective paradigm emphasizes viewers' perception and emotion of the landscape. The analysis methodology can be flexible and individual without being limited by any structured framework or specific criteria and characterized by specific details.

In practice, objective and subjective paradigms are usually integrated into the Multi-Criteria Decision Making (MCDM) framework, Analytic Hierarchy Process (AHP), and Contingent Valuation Method (CVM) in site selection [27]. More specific methods, like the Fuzzy Analytic Hierarchy Process (FAHP), are applied to obtain the different weights of the criteria and evaluate the alternatives [28]. Sowińska-Świerkosz and Chmielewski discuss the methods of choosing reasonable indicators for landscape visual assessment [29]; Del Carmen Torres Sibille et al., approach the wind farm site selection and landscape protection by using a multi-criteria comprehensive assessment method [30]; the planning authorities in the United Kingdom have rich experiences in heritage and landscape protection, and have published specific guidelines dealing with landscape and wind farm planning [31]. The following are the three typical methods broadly used by various governments for assessing landscape visual impact in wind farm projects.

For protecting the visual landscape resource, a number of countries published guidelines to standardize the process of landscape visual impact assessment for wind farm planning [34][35][31]. The quantitative assessment methods put forward by Nohl, and improved by Paul et al. and Roth have been popularized for calculating the compensation area and fees [15][36][18]. Some multi-criteria, decision-making systems are set up for comprehensive planning targets, combining aesthetic knowledge, spatial analysis, and statistical methods to achieve more precise and reasonable conclusions of visual assessment and reasonable planning [37][38][11][39].

However, most landscape visual impact assessments for wind farms are result-oriented, deriving the results of wind turbines viewshed, instead of the reason causing visual impact. Indeed, the visual impact comes from wind facilities. But the mechanism of visual perception and visual impact can be researched to find out the influencing factors of visual impact. This paper attempts to investigate the visual impact and its correlated factors at different scales, which helps to explore definite solutions for visual impact mitigation.

III. METHODS

This research is based on the case study of Zhongying Wind Farm, located in the mountain area of Ningbo City, Zhejiang Province of East China (Fig.1). It is a typical rural wind farm surrounded by villages, farmland, forests, and tea gardens with a dense population nearby. A total of 18 WD103-2500T wind turbines have been installed on the ridge of Fuquan Mountain at altitudes of between 140 and 450 m, which causes serious visual impact, landscape deterioration, and influence on recreational visits. The visual intrusion, attached to other environmental impacts, arises the fierce social opposition and disapproval, especially from close-by villages. However, the landscape visual impacts are not explicitly the declining functions of distance, which change with various factors and their interaction relationship. This paper aims to explore the key factors influencing visual impact under different distance groups.

Through the pre-study of literature and field trip, a questionnaire sheet is designed based on the classification of distance from residents to the wind turbines to dig out the key factors in different distances. In the questionnaire, the degree of visual impact is asked to score as the dependent variable with an 11-point Likert-type scale (i.e., 0: serious impact, 10: no impact). Additionally, the related factors of visual impact collected from pre-investigation are listed in the questionnaire as independent variables as listed in Table 2. The data are processed by analysis of variance (ANOVA) and linear regression analysis through SPSS with four distance groups: 1) within 1 km; 2) 1 to 2 km; 3) 2 to 4 km; 4) above 4 km. Recommendations for landscape planning and visual impact mitigation solutions are put forward according to the statistical analysis in each distance group.

Classification	Objective methods	Subjective methods
Basic value	Aesthetic and ecological value of landscape	Public preference and landscape perception
Methodology	Multi-Criteria Decision Making (MCDM) framework AHP Contingent Valuation Method (CVM) Fuzzy Analytic Hierarchy Process (FAHP)	Preference model Scenic Beauty Estimation procedure (SBE) Law of Categorical Judgment (LCJ) SD
Paradigm	Expert paradigm	Psychophysical paradigm Cognitive paradigm Experimental paradigm
Representative literatures	(Lewis, 1964; Litton, 1968, 1974; Magill & Litton, 1986)	(Daniel & Boster, 1976；Buhyoff et al., 1978; Buhyoff et al., 1979)
Characteristics	Structural, practical, conscious,	Flexible ,individual, full of specific details
Relationship with viewers	Not including	Mainly including the perception and emotion of viewers
Classification	Objective methods	Subjective methods
Participants	Expert group consists of planners, ecologists, aesthetic experts, etc.	Expert group, community, the local planning authority, public

Table 1 Comparison of landscape visual assessment methods.

Figure 1. Location of Zhongying Wind Farm. (Source: ArcGIS Earth)

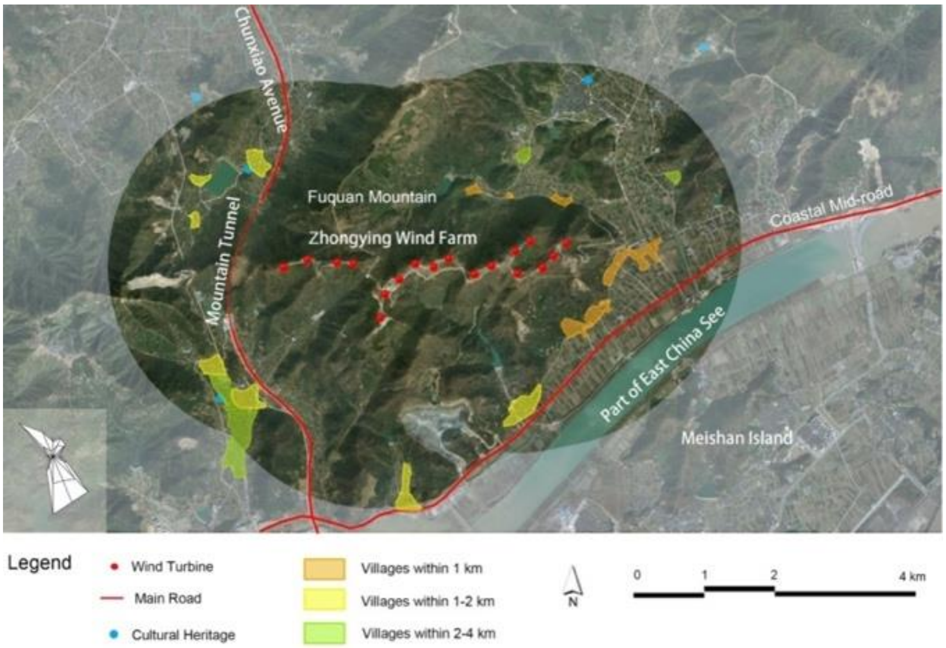

Figure 2. Distance groups category of Zhongying Wind Farm (Source: edited by authors)

IV. RESULTS

A. Data Collection and Preprocessing

The research team interviewed random sampling across 17 villages and rural areas around Zhongying Wind Farm of 180 respondents, with 169 valid samples returned. These samples were randomly selected across the research region to keep balancing samples between four distance groups.

B. One-Way Analysis of Variance

The data collected through questionnaires were processed in the following steps. Firstly, a total of 10 factors were divided into three categories according to their attributes and interaction with visual impact : WT-related variables, environment-related variables and respondent-related variables. The correlation between each independent variable (influencing factors) and dependent variable (visual impact) was detected by the one-way analysis of variance. In Table 2, it can be noted that among 10 variables, 7 variables were statistically significant. Dynamic rotation (F=97.728), aesthetic change (F=32.903), shadow flicker (F=29.121), visibility (F=27.331), and size of WTs (F=20.235) are statistically significant to the dependent variable, visual impact for wind turbines. Factors of ecological function degradation (F=15.975) and length of residence (F=9.757) are also significant with a lower F value. Factors of the number of WTs, original environment quality, and individual Eyesight are not correlated to visual impact from a statistical perspective since their P-values are over 0.05.

Table 2. Variance analysis of correlations between potential factors and visual impact

Variables	Categories	F (ANOVA)	P (Significance)
WT-related variables			
Dynamic rotation	1: quick; 2: medium; 3: slow	97.728**	0.000
Shadow flicker	1: very serious; 2: medium; 3: no feeling	29.121**	0.000
Size of WTs	1: too huge; 2: acceptable; 3: not huge	20.235**	0.000
Number of WTs	1: too many; 2: medium; 3: few	1.494	0.228
Environment-related variables			
Original environment quality	1: high; 2: medium; 3: low	0.112	0.894
Ecological function degradation	1: serious degradation; 2: acceptable degradation; 3: little/no degradation	15.975**	0.000
Visibility	0: invisible, 2: partly visible, 3: most visible, 4: totally visible.	27.331**	0.000
Aesthetic change	1: seriously changed; 2: acceptable change; 3: little or no change	32.903**	0.000
Respondent-related variables			
Individual Eyesight	1: good; 2: general; 3: poor	2.122	0.123
Length of residence	1:＜5, 2: 5-10, 3: 10-20, 4:＞20. (years)	9.757**	0.000

Note: * $p \leq 0.05$, ** $p \leq 0.01$.

C. Linear Regression Analysis

The second step is to introduce all the statistically significant variables into linear regression by distance category to tease further relative significance of each variable in each distance group and detect whether the correlation variables in each group change with the distance growth. The regression analysis is separately conducted by distance groups, with the same dependent variable, visual impact of wind turbines. The statistically significant variables (n=7) in the variance analysis are selected as independent variables. As Table 3 illustrates, four linear regression models were run with statistically significant variables.

In Group 1 (distance below 1 km), the score of visual impact is 2.39 within 0 to 10 scaling, referring to serious impact degree. Among the correlated variables, only the variable of dynamic rotation and length of residence were statistically significant ($P \leq 0.01$.). In Group 2 and Group 3 (distance from 1 to 4 km), the score of visual impact given by respondents is 5.39 and 5.78 respectively. The factor ecological function degradation ranks first as the most significant independent variable, which reveals that the respondents' attitude toward visual impact is highly influenced by local ecological service. In Group 4 (distance above 4 km), the visual impact score is 6.21. With the distance growing and less physically environmental impact, the focus of visual impact turns to the factor of aesthetic change.

V. DISCUSSION

A. Visual Perception and Visual Impact

Visual landscape refers to the visual expression of the elements, structure, and functions of landscape [40]. The connotation of "landscape" includes the visual perception of landscape, as well as other sensory and ecologic, economic, and functional aspects of landscape. Broadly speaking, landscape refers to all the characteristics of the earth's surface. Therefore, the influencing factors of landscape visual impact do not merely derive from the visual impairment from wind turbines, but also include the socio-demographic factors and surrounding environment. With three dimensions of factors involved in this research, the visual impact can be explained under the generalized visual landscape connotation.

Visual perception dominates the sensory with 87% of the sensory information, while the other 13% (e.g., auditory, olfactory, tactile) is assisted from other dimensions to confirm and reinforce the information [41]. Both in terms of information volume and spatial extent, visual perception is the most important sensory source for information, which also influences behavior, preference, and aesthetics in landscape research. It has also become an instrument in landscape protection, monitoring, and planning [42]. Visual perception is itself a complex information processing mechanism related to physiology, psychology and social attributes of human beings [43]. Notably, not all perceptional information has an impact, only if it exceeds a certain threshold that depends on the stimulus intensity of the object and the sensitivity of the observer. Viewers' responses can be classified into two types: visual perception threshold (whether people can see the object) and visual impact threshold (whether people feel themselves being influenced by the object). The visual perception threshold (detection and recognition) relies more on viewers' physiological perception capacities, which are measurable as above mentioned, rather than cognitive mechanism (psychological and social perception). The visual impact threshold is more challenging and subjective to obtain, which depends on viewers' subjective judgment criteria and differs largely from person to person, and from society to society [44].

Table 3. Results from linear regression of community acceptance for wind turbines

Independent variable	Group 1	Group 2	Group 3	Group 4
Dynamic rotation	1.914**	0.531	0.339	0.164
Shadow flicker	-0.129	0.030	0.163	-0.457
Size of WTs	-0.603	0.407	-0.105	-0.088
Ecological function degradation	0.250	1.655**	0.752**	0.490
Visibility	-0.598	-0.385	-0.437	-0.664
Aesthetic change	0.656	0.204	0.590**	1.220**
Length of residence	-1.093**	-0.116	-0.192	-0.169
Constant	4.804	0.974	3.761	5.079
R2	0.722	0.516	0.563	0.464
N	49	46	37	37

Note: [a] Constant values by model use unstandardized coefficients. All others use standardized coefficients.
* $p \leq 0.05$, ** $p \leq 0.01$.

B. Visual Impact and Distance

This paper attempts to explore the relationship between the correlation factors of visual impact and distance. According to the regression analysis, dynamic rotation speed of wind turbines' blades and length of residence for the respondents are both the key factors affecting the visual impact within a close distance. However, referencing the visual impact threshold theory, the former factor is more inclined to the physiological perception threshold, while the latter factor belongs to the category of cognitive mechanism (psychological and social perception). During the local investigation, the residents complained about the linkage effects caused by the huge blade rotation: noise, dizziness and the sense of insecurity. Shang and Bishop [44] point out that dynamic WTs are about 10 to 20% larger in their size in visual perception than the size of the static ones. As the distance grows, the viewshed area of wind turbines declines, and direct visual impact is not a dominant factor again. At medium and large spatial distances, ecological function degradation and aesthetic change are the main factors affecting the visual impact. The opponents concentrate on local ecological function disruption, especially harming the nearby flora and fauna, causing soil erosion and water pollution during the construction and operation process [45][46]. From the perspective of aesthetic, the huge size and technological impression spoil the original landscape character [47].

C. Recommendations

When the landscape suffers impairment, replacement is suggested on the same site or near the proposal project, to recover the whole environmental quality to some extent. Such compensation is not only possible through a similar restoration of the status quo, but also through a "landscaping-appropriate redesign". Landscape redesign is mandatory in the aesthetically significantly impaired space and the immediate vicinity of the intervention site. It is worth mentioning that a slight difference from the original landscape is allowed, as long as the essential features, elements, structure, and functions are guaranteed.

VI. CONCLUSION

In China, the growing demand for wind energy complies with the carbon neutrality strategy. While the rapid expansion of wind farms exacerbates environmental impacts, especially in dense population areas. Among all the negative impairments, visual impact is highly subjective and uncertain, making quantitative assessment difficult. This paper investigates the factors related to the visual impact of wind farms in rural areas in the eastern coastal area of China through the questionnaire, one-way analysis of variance and regression analysis. The results reveal that the visual impact does not decay with distance in a linear function. Further, the highly correlated factors of visual impact change with distance growth. In close-distance, dynamic elements are the key factor, followed by ecological function degradation in mid-distance, and aesthetic change in the long-distance. It is recommended to formulate compensation strategies under different buffer distances. The outcomes help to optimize the landscape planning and compensation implementation for wind farms. In the long run, this study seeks a feasible solution for balancing regional wind power development and environmental resource protection.

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