Applied Energy 151 (2015) 23–31

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Wind turbines location: How many and how far?

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HIGHLIGHTS

- Negative impact of wind turbines (WTs) diminished with distance from observer.
- Impact disappeared at 5–10 km with respect to landscape's aesthetic quality.
- Negative effects increased with number of WTs in an approximately linear manner.
- A cumulative effect of higher numbers of WTs was not confirmed.
- Distance and numbers interacted significantly with landscape aesthetic quality.

ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form 24 March 2015
Accepted 15 April 2015
Available online 29 April 2015

Keywords:
Visual impact
Landscape quality
Visual preference
Wind power
Renewable energy planning

ABSTRACT

Existing research relating to visual impact of wind turbines (WTs) affirms this to be an essential parameter for public acceptance in most cases as well as for the planning process and permitting of planned wind farms. This study brings new findings about the impact of two crucial factors: numbers of WTs (1–25) visible and distances of WTs (0.75–15 km) from the observer (e.g. from residential buildings, landmarks, observation points). Photographs of three aesthetically varying landscapes with various numbers of WTs (Vestas V90, height 105 m, rotor diameter 90 m) at various distances were evaluated in terms of visual preferences. The results show significant effect from the aesthetic value of a given landscape on the impact of both tested factors. An important finding is that the landscape with the highest aesthetic quality initially was evaluated to be the absolute worst after the addition of WTs and vice versa. Increasing numbers of WTs in the least attractive landscape had less visual impact than did doing so in the two more attractive landscapes. This helps explain strong public opposition to locating WTs in aesthetically valuable landscapes and their greater acceptance in less-attractive landscapes. Increasing stepwise from 1 to 25 WTs within a given landscape progressively decreased visual preferences, although the cumulative effect of a higher number of WTs was not confirmed. We also established threshold distances after which the negative visual impact of a WT disappeared (10 km for the most attractive landscape, 5 km for the least attractive one). Based on these findings, visibility zones were proposed for practical assessment of WTs' visual impact. The study's results can make a substantial contribution towards reducing negative visual impact in WT planning and thus achieving greater public acceptance of these devices.

1. Introduction

Visual impact has become the most distinctive among public perceptions of wind turbines (WTs), ranking higher than such other environmental concerns as the impact on bird populations [1] and noise annoyance [2]. According to the Ministry of the Environment of the Czech Republic, for example, 85% of proposed wind farm projects in the country have been cancelled due to their visual impacts. Despite the obvious importance of visual impact, public authorities still lack understanding regarding the inter-relationships between WT placement, landscape, and public perceptions.

Considering that rapid development of wind energy is one of the main means of reaching renewable energy targets and that negative public attitudes are emerging, there is a need for comprehensive research on visual preferences regarding wind turbines and associated influencing factors. Existing research findings on the visual impact of WTs indicate two general types of variable factors influencing the visual assessment of WTs. These can be termed "physical attributes" and "respondents' characteristics". Molnarova et al. [3] reviewed the main papers focused on visual assessment, and almost

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http://dx.doi.org/10.1016/j.apenergy.2015.04.060
0306-2619/

all of those studies allude to respondents' characteristics. Meanwhile, other factors have not yet all been rigorously evaluated. The main characteristics of respondents have been identified as socio-demographic (gender, age, education, general attitude towards wind energy), occurrence of WTs near the respondents' homes, daily contact with WTs [4], and prior experience with WTs [5].

In order to understand public behaviour, papers often refer to the phenomenon of NIMBYism (Not In My Backyard), which has been analysed due to the many cases of wind projects being rejected in certain areas [6–9]. This issue was reviewed by Petrova [10], who explained the reasons for opposition to establishing WTs. Petrova concluded that the NIMBY syndrome does not adequately explain visual and landscape concerns. Most often the reasons for opposition are aesthetic degradation and visual impact, in which cases it is more important to consider the affective and symbolic association of these structures with the landscape. The NIMBY effect has been the background motive for most research on WT acceptance, and it has consisted of case studies analysing the preferences for WTs already erected or for those planned in selected regions and comparing the evaluation of inhabitants living at various distances from wind parks [11–13]. In addition, recent studies have been based also on choice experiments whereby respondents select from several presented possibilities that option most tolerable for them with regard to their acceptance of new wind farms locations [14,15].

The major physical attributes of importance, meanwhile, include the characteristics of the WTs themselves (height, number, colour, rotor diameter and moving blades), landscape qualities, and distance from the observer. Specifically, distance from the observer means distance from such visually sensitive areas and structures as residential and recreation buildings, cultural features, and landmarks.

The research has quite often taken into consideration awareness of the imposing size and height of these structures. The height factor has been analysed in most studies, predominantly with an emphasis on cumulative effect and interaction with numbers of WTs. Warren et al. [16] and Devine-Wright [8] found that the public has a clear preference for smaller wind farms, even if this means having more than one wind farm in a given locality. Moreover, people prefer reducing the number of turbines by replacing smaller turbines with larger ones even though larger ones might be visible from a larger number of residences [4]. Other results show a less positive attitude for more than five on-land turbines and a cumulative effect for five turbines encountered per day in long thresholds [17]. Research in Denmark demonstrated similar findings. Replacement of 400 old turbines with 50 new, larger ones did not increase the overall visibility of wind turbines in the region. Long-range visibility caused by the smaller turbines was reduced while the short- to middle-range visibility of the large turbines was amplified [18].

Compared to the amount of research done on numbers of wind turbines, only a few studies have so far evaluated the distance factor as a visual threshold. Moreover, the results for those studies are diverse and no clear conclusion for the role of this attribute has yet been established. Research in South Australia, for example, did not substantially prove a reduction of negative visual effects of a wind farm with greater distance [19], whereas research in the Czech Republic showed a positive relationship between visual preferences and increasing distance [3]. A recent study by Vries et al. [20] found that distance decay of impacts is stronger for barns and business parks than for turbines. The maximum distances at which wind turbines can still be distinctly perceived (in this case a wind turbine on a tower 50 m high with a 3-blade rotor having blades 26 m long) were determined by Bishop [21] to be 10 km in "ideal" conditions (clear visibility and stormy sky) and 6 km in prevailing conditions (slightly hazy, sky other than stormy). In view of their rapid development and increasing size, turbine towers 100 m tall are today considered to be usual, and so the relevance of these findings may not fit the current state of the art. A usual methodology for assessing the impact of vertical structures on landscape character takes an approach similar to that of visual thresholds and barriers to determine the so-called Affected Landscape Area. Application of the methodology involving visibility zones as a general approach could be used in any situation [22]. Other studies detecting the visibility are using, for instance, GIS methods [23,24] or other visibility software [25]. Although the distance factor remains an open issue in relation to visual assessment of wind parks, it is a factor needing to be incorporated into research with a detailed focus on determining thresholds and its relationships to other factors.

The public perception of WTs might be influenced by such other attributes as the aesthetic and visual quality of the landscape where they are to be located. Type of landscape has been determined to be an important factor in visual assessment of a landscape in which a turbine is situated [26], although just a few papers have verified this affirmation. Research in the Netherlands has unambiguously shown minimal acceptability for turbines in wetlands of a natural protected area, that landscapes with mountainous morphology and natural elements are considered to be more beautiful, and thence that siting the structures in such areas would be less welcome [27]. Similarly, research in South Australia has tested 68 coastal and inland locations where wind farms could be located, both without wind farms and with wind farms digitally added to the scene. Wind farms were generally viewed as having a negative effect on landscapes of higher scenic quality but a positive effect on landscapes of lower scenic quality. The study concluded that wind farms should avoid areas of higher perceived scenic quality, particularly on the coast, and be located in areas of lower scenic quality [19,28]. Research in the Czech Republic has shown significantly stronger preferences for wind turbines in landscapes of low visual quality than in visually attractive landscapes [3,29]. Vries et al. [20] confirmed that wind turbines have always had a considerable negative impact on scenic beauty, especially when the landscape is considered to be very attractive.

Although each of the physical attributes distance from the observer, number of WTs, and type of landscape has been tested separately and affirmed to be a significant factor, there is still a lack of dimensional research on consistent evaluation of these attributes. In order to understand the interaction between these factors, research needs to be undertaken which uses comprehensive statistical analysis to explain various situations which can be very changeable. A proposal that might be accepted in one type of landscape, for example, might be rejected in another one. Consequently, the goal of the present study was to verify and furthermore specify the effect of distance from the observer and number of WTs located in various landscapes on the perception of those landscapes. Regarding distance from the observer, the aims were to (1) establish whether and how the impact of increasing distance on visual preferences of landscapes changes, and (2) determine distance thresholds after which the negative visual impact of WTs disappears. In terms of WT numbers, the aims are to (3) find out how increasing numbers of WTs influence the visual preferences of landscapes, and (4) establish if the cumulative effect could be affirmed from the perspective of visual preferences, which could abruptly decrease the visual preferences beyond a certain number of WTs. An additional objective of this study was to (5) analyse the effect of interaction between number and distance of WTs on visual preferences of aesthetically varying landscapes.

2. Materials and methods

2.1. Study design

The study examined visual preferences for three different landscapes (A, B, and C) of varying aesthetic quality. It was designed to collect new data determining the effects of WT distance from the observer and of the number of WTs. Photographs used in the survey were taken with a digital camera having a basic focal length of 50 mm during a summer day with clear weather conditions. For the photomontages, Adobe Photoshop was used to digitally add to each image one of the most common types of WT recently being setup in Central Europe – the Vestas V90 (with hub height 105 m, rotor diameter 90 m). Examples of several situations with and without WTs are shown in Fig. 1. The positions of the blades were rotated differently in order to obtain a realistic photomontage. Evaluation was setup using a 15-point assessment scale from +7 to −7, with 0 representing a neutral attitude, "+7" the most positive one, and "−7" the most negative attitude. Simple questionnaires were developed for respondents to fill in a rating value for each correspondingly numbered picture. The choice of rating value was intended merely to answer the question, How do you like this picture?

To examine all three factors (distance of WTs from the observer, number of WTs, and landscape visual quality), the research was divided into two experimental parts. The goal of the first experiment was to analyse visual preferences for distance of a WT from the observer (Fig. 1b–e shows examples of WT added at several distances). For this purpose, one single turbine was digitally added to each image at several distances: 750 m, 1.5 km, 3 km, 5 km, 7.5 km, 10 km and 15 km. This made a set of 21 modified photographs (3 × 7) plus 3 unedited photographs in order to have an evaluation of the turbineless landscape for comparison. The selected distances reflected an established methodology for impact assessment on landscape character [22] and previous research undertaken at Czech University of Life Sciences [3]. The second experiment focused on the number of turbines (1, 5, 10, 15, 20, and 25), which were visualised at distances of 1.5 km and 5 km and always with turbines 300 m apart from each other (Fig. 1f–i). This consisted, then, of a set of 36 photographs (2 × 3 × 6) plus 3 photographs without turbines. The chosen numbers of WTs correspond to the arrangements of existing wind farms in the Czech Republic [30,31] and other countries [4,18]. The distances of 1.5 km and 5 km represent short-range and middle-range distances [3,21], for which strong and middle-strong visibility for the turbines was presumed.

The photographs were randomly ordered in both sets to avoid their presentation from the least number of WTs to the most, as well as from the closest to the furthest, as that could lead to a poorer evaluation caused by the "growing effect". Simultaneously, the pictures of landscapes with no turbines were randomly placed within each set. Images were evaluated by two relatively homogenous groups of respondents, both composed of university students. Whereas the first group was made up of students from biological and

Fig. 1. Example photographs used in the survey. Image a. is an unedited photograph of landscape A. Images (b–i) – present examples of adding wind turbines (WTs) to the starting image. Image (b). – landscape B with one WT digitally added at a distance of 0.75 km. Image (c) – landscape C with one WT digitally added at a distance of 1.5 km. Image (d) – landscape A with one WT digitally added at a distance of 5 km. Image (e) – landscape B with one WT digitally added at a distance of 10 km. Image (f) – landscape C with five WTs digitally added at a distance of 1.5 km. Image (g) – landscape A with 25 WTs digitally added at a distance of 1.5 km. Image (h) – landscape B with five WTs digitally added at a distance of 5 km. Image (i) – landscape C with 25 WTs digitally added at a distance of 5 km.

ecological programmes at Czech University of Life Sciences, the second group comprised students in civil engineering and technical programmes at Czech Technical University. The survey was undertaken in 2013. Images were projected onto a screen in a lecture hall to groups of students totalling 169 respondents. In order to ensure an equal response time for the pictures, each image appeared on the screen for precisely 10 s.

The photographs of the landscapes were selected to reflect varying aesthetic and visual quality. Landscape A is a part of the České Středohoří Protected Landscape Area, characterised by typical mountainous terrain, treeless hills, a high proportion of natural elements, rich land cover in its comparatively small scale, and minimal human impact. The land cover consists of several types of small-scale vegetation which compose a visually contrasting mosaic in colour pattern and attractive scenic view. Landscape B is located around Želiv, Central Bohemia. It has an intermediate scale and combines agricultural and forest landscapes with less distinctive morphology. There are greater human influences, but these are still in balance with the natural elements. Land cover is defined by larger fields, meadows and forests. The mosaic is less rich in vegetation types. Landscape C, around Neratovice, Central Bohemia, is intensively exploited lowland dominated by human impact and man-made structures and with a relatively low presence of natural elements. Land cover consists predominantly of large fields and urbanised area. There is rather little variation in contrast and colour, and so the impression is rather monotonous and featureless.

2.2. Data processing

The effect of one WT placement at various distances from the observer on landscape perception (the goal of the first experiment) was analysed using generalised linear mixed models (GLMM). These models work with two types of categorical explanatory variables – those with fixed and random effects. In our study, the variable with random effects is the identification of the respondent (see below). To avoid pseudoreplication, GLMM should be used in experiments with temporal or spatial correlation in the data or in cases (as in our case) of repeated measurements [32].

Within GLMM, we used the *glmer* function, which is a part of the *lme4* package of R statistical freeware, version 2.15.0 [33]. Each respondent provided ratings of 24 photos (seven distances plus a control landscape without any WT for each of the three landscape types). Landscape perception (i.e. respondents' ratings of the photos; $n_{\text{resp.}} = 169 \times 24$ ratings = 4056 rows) represented in our model a semi-quantitative response variable on a 15-point assessment scale (from −7 to +7, including zero). This variable was converted into a variable with a binomial distribution comprising two vectors – the real landscape assessment value of each respondent and the supplement to the maximum evaluation value. For example, if a certain landscape assessment by any person was +5, the supplement to the maximum evaluation (+7) was 2. The value +5 represents here success, i.e. how the particular respondent liked the landscape, and the supplement 2 represents failure (the higher this value, the lower is the assessment). Likewise, if the respondent gives an evaluation of −2, the supplement is 9. Following the rules for modelling with binomial errors (according to Crawley [32]), we used the cbind function and bound together the two aforementioned vectors of the response variable into a single object *y*. This object *y* was then used in GLMM analyses as the response variable with a binomial distribution. The distance of WTs from an observer, as the quantitative variable (seven distances and a control landscape), landscape type (nominal variable with three levels – landscapes A, B and C), and the interaction between these two variables comprised the explanatory variables in our model. As mentioned above, each respondent evaluated 24 different photographs. To avoid pseudoreplications, the identification of the respondent was included as a random factor in the model and GLMM were therefore used. Using GLMM and the identity of respondent as a random factor, we also solved the potential problem of differing evaluation among respondents according to their school and other characteristics.

Table 1
Effect of wind turbine (WT) distance, WT number, type of landscape, and interactions of these variables on landscape perception. All assessed variables were found to be significant.

Variable	χ	df	p
Number of WTs	2047.20	1	$<10^{-6}$
Distance of WTs	1081.30	1	$<10^{-6}$
Landscape	69.51	2	$<10^{-6}$
Landscape: numbers	155.29	2	$<10^{-6}$
Landscape: distance	73.19	2	$<10^{-6}$
Distance: numbers	9.64	1	0.002

To analyse the interaction between the distance and number of WTs (second experiment), we used the same statistical procedure as in the first experiment (i.e. GLMM with the respondents' ratings as response variable). The distance of WTs from the observer (1.5 or 5 km, nominal variable) and the number of WTs (1, 5, 10, 15, 20 or 25, quantitative variable) constituted the model's explanatory variables. Because the experiment was run with three landscapes (A, B and C), the effect of landscape type and all possible double interactions, including the target interaction between the distance and the number of WTs, were also analysed (Table 1).To avoid pseudoreplication, the identification of the respondent was again included as a random factor in the model.

The significance of each explanatory variable in both models was analysed by deletion tests, using backward selection procedure. The final models, consisting of only significant variables, were checked in the end using standard statistical diagnostics [32].

3. Results

3.1. Effect of WT distance

In the first experiment with one WT situated at different distances, we found that the distance of WTs from the observer significantly affected the perception of the assessed landscapes ($\chi = 870.25$, df = 2, $p < 10^{-6}$). The farther away the WT was situated, the more positive was the image's evaluation. Those landscapes without any WT were assessed with the highest ratings. Since the experiment was deliberately performed using three different landscapes (A, B, and C), we also analysed the interaction between the distance variable and the type of landscape. We found that the perception of a WT varied at different distances according to a landscape's aesthetic quality. Whereas the perception of WTs at different distances was similar for landscapes with high aesthetic quality (A and B), and with a positive effect of increasing distance, the perception of WTs in a less-attractive landscape with stronger human impact (C) was less influenced by distance. The difference in evaluation between photographs with WTs at the closest (750 m) and furthest (15 km) distances was more than twice as great for landscapes of higher aesthetic quality ($A_{\text{dif}} = 7.17$, $B_{\text{dif}} = 7.00$) compared to the unattractive landscape with distinctive human influence ($C_{\text{dif}} = 3.28$).

Images of landscapes with one WT at a distance of 750 m were perceived very similarly, regardless of the aesthetic quality of the landscape (mean evaluation: $A_{0.75\text{km}} = -2.67$, $B_{0.75\text{km}} = -2.92$, $C_{0.75\text{km}} = -2.79$). The perception of landscapes with the WT at a distance of 1.5 km was substantially more positive (around 2 points higher for all landscapes) compared to the closest distance

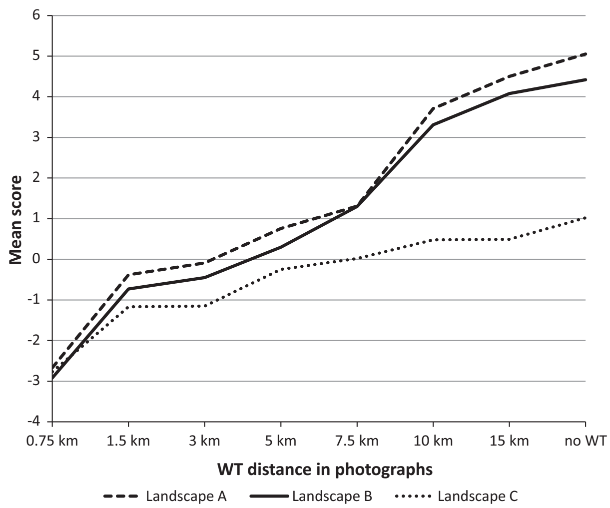

Fig. 2. Effect of distance from observer of a single wind turbine (WT) on perception of a landscape. At right of horizontal axis, "no WT" refers to the reference value for a landscape without WT.

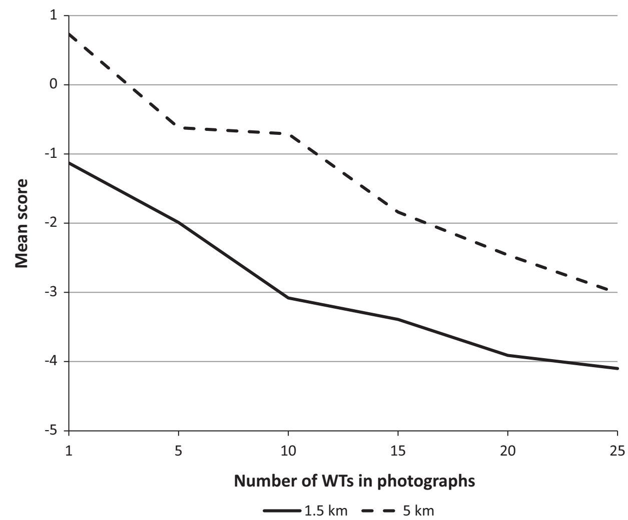

Fig. 3. Interaction plot of distance and numbers of wind turbines (WTs) showing different perception scores (mean score, vertical axis) for various numbers of WTs (number of WTs in photographs, horizontal axis) at two assessed distances from the observer (1.5 and 5 km).

of 750 m. The more attractive landscape had concurrently greater improvement in its perception (Fig. 2). The evaluation of landscapes A and B increased rather slightly between 1.5 and 7.5 km with the distance of the WT, but a major shift in the perception of landscapes with the WT (A and B) occurred in between the distances of 7.5 and 10 km. At that distance point, the scores for both landscapes A and B amplified sharply. Regarding landscape C, this shift is less evident and can be distinguished at a closer distance, between 3 and 5 km. The evaluations of all landscapes with one WT at distances of 10 km and greater very closely resemble the assessments of the landscape without WT (Fig. 2). We concluded that from the visual point of view one WT ceases to reduce visual preferences beyond a distance of 10 km for higher-quality landscapes (A and B), whereas for the less-attractive landscape C this point is even closer, around 5 km.

3.2. Interaction between distance and numbers of WT

Whereas the first experiment analysed the impact of distance for one WT, the goal of the second experiment was to test the interaction between WT distances from the observer and number of WTs. Therefore, we assessed the perception of various numbers of WTs (1, 5, 10, 15, 20 and 25) at two distances (1.5 and 5 km).

The impact of WT distance on the evaluation was highly significant (Table 1). Regardless of their number, WTs were perceived at a closer distance (1.5 km) more negatively ($mean_{1.5km} = -2.93$) than at a distance of 5 km ($mean_{5km} = -1.33$). The impact of WT number was the most significant of the tested variables, irrespective of distance from the observer. The higher the number of WTs, the more negative the score (Table 1, Fig. 3).

We also found the interaction between numbers of WTs and distance to be significant (Table 1). Visual preferences diminished with increasing numbers of WTs at both tested distances. This diminution did not have a uniform character (Fig. 3), however. At distance 1.5 km, the score's decrease was steady and relatively steep from 1 to 10 WTs. When the number of WTs was greater than 10, the decrease was less striking. In particular the evaluation of 20 versus 25 WTs did not essentially differ ($mean_{20WT1.5km} = -3.91$ vs. $mean_{25WT1.5km} = -4.10$). In any case, WTs from 10 and up were perceived as a significant source of deterioration at such a close distance. A different situation existed, however, for the distance of 5 km. In this case, the most significant decrease in the evaluation was determined already between 1 and 5 WTs, while the ratings between 5 and 10 WTs did not really vary statistically ($mean_{5WT5km} = -0.62$ vs. $mean_{10WT5km} = -0.71$). Somewhat in contrast to the nearer distance, the following increase in WT number up to the maximum tested amount of 25 WTs led to a relatively steady and steep diminution in score. Although lower numbers of WTs (between 5 and 10) could be perceived rather equivalently at the further distance, the increasing number of WTs up to 25 was nevertheless discernible (Fig. 3).

3.3. Effect of landscape aesthetics

All three landscapes (A, B, and C) were assessed differently (Table 1), and furthermore this evaluation varied if WTs were or were not situated in the landscape. The assessment of photographs with WTs –regardless of their number and distance from the observer – was the most negative for the most attractive landscape A having the most natural character ($mean_{A\_WT} = -2.42$). The other landscapes B and C with WTs added were evaluated very similarly (respectively, $mean_{B\_WT} = -1.98$ and $mean_{C\_WT} = -2.00$). An entirely different situation occurred in assessing landscapes without WTs, wherein landscape A had the most positive score ($mean_A = 5.52$). Landscape B also had a highly positive score ($mean_B = 4.83$), whereas landscape C (the least attractive one) without WTs had a substantially lower score ($mean_A = 1.93$). The location of WTs was crucial in our findings since the greatest visual impact of WTs on landscape aesthetics was demonstrated in attractive landscapes with natural character, where the decrease of aesthetic evaluation was the most significant (Fig. 4). In contrast, the aesthetic deterioration was much less for landscapes which were not considered to be particularly attractive to begin with.

The landscape aesthetic quality was also determined to be an important factor in interactions with the number of WTs and distance from the observer (Figs. 5 and 6). Our findings show significant interaction between landscapes and distance (Table 1). WTs (regardless of their number) at a closer distance of 1.5 km are perceived as especially disruptive in the most attractive landscape A, while the evaluation of WTs for the other two landscapes (B and C) was similar and less severe (Fig. 5). At a distance of 5 km, the difference in perception according to the landscapes' aesthetic quality was not very pronounced. The results also implied a

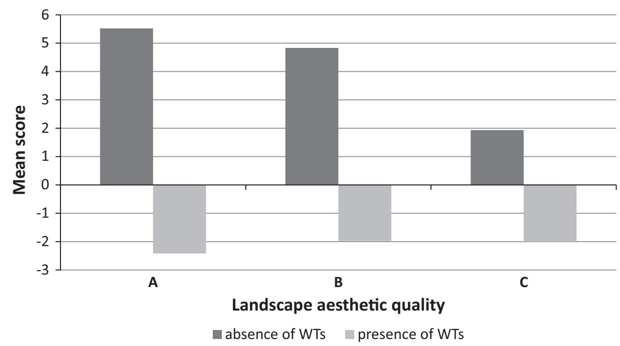

Fig. 4. Perception (mean score, vertical axis) of three assessed landscapes (landscape aesthetic quality, horizontal axis) according to the absence (dark grey columns) and presence (light grey columns) of wind turbines in the photographs.

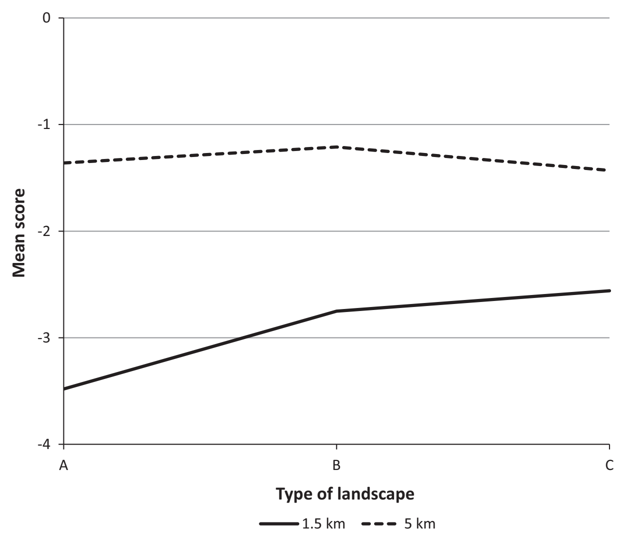

Fig. 5. Interaction between landscapes (landscape aesthetic quality, horizontal axis) and distance of wind turbines (1.5 and 5 km) from the observer.

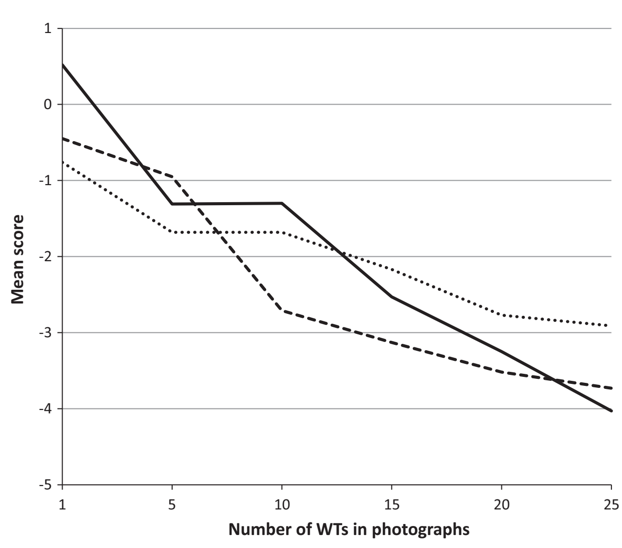

Fig. 6. Interaction between landscapes according to their aesthetic quality and number of wind turbines (number of WTs in photographs, horizontal axis).

difference in perception between distances of 1.5 and 5 km (regardless of the number of WTs). This difference was greatest for the most attractive landscape A ($A_{dif1.5\_5km}$ = 2.12), lower for B ($B_{dif1.5\_5km}$ = 1.54), and lowest for the least attractive landscape C ($C_{dif1.5\_5km}$ = 1.13).

The interaction of WT number and landscape aesthetic quality (regardless of the distance) was likewise significant (Table 1). The decrease in evaluation with increasing number was evident for all tested landscapes, although this trend was seen to differ substantially depending upon the landscape type (Fig. 6). The greatest difference in landscape perception with the lowest (1) versus highest (25) number was found for landscape B (B_{dif1_25WT} = ca 4.55). This different was smaller for landscape A (A_{dif1_25WT} = ca 3.28) and least of all for landscape C (C_{dif1_25WT} = ca 2.15). Increasing numbers of WTs thus had the lowest visual effect on the perception of the least attractive landscape having higher human impact and fewer natural elements.

4. Discussion

This study's results indicate a significant impact of all tested factors (i.e. number of WTs, their distance from the observer, and the aesthetic quality of a landscape) on visual preferences. From our earlier study [3] and other studies [21,34,35], it is apparent that these attributes are crucial factors in most situations regarding public acceptance of WTs. The aim of this study was not just to replicate earlier research, however, and thus to reconfirm this determinative impact. Rather, it was to quantify ranges of these factors and, if possible, to establish their threshold values.

4.1. Effect of WT distance and visibility zones

In the case of a single WT placement at distances of 750 m to 15 km from the observer, landscape attractiveness was continuously reduced for each evaluated photograph. The closer the WT was situated to the observer the lower preferences which were found for this landscape. However, this gradient was not wholly linear.

An interesting finding concerns the perception of a WT at a distance of 750 m in all evaluated landscapes. Although the evaluation of landscapes with WTs at greater distances was significantly different for the more attractive landscapes (maximum scores +4.4 and +4.3 for A and B, respectively) and the less attractive one (maximum score +0.2), it essentially did not differ at the shortest distance (ranging between −2.7 and −2.9). These results confirmed the dominance of such a closely situated WT in any landscape. The WT's proximity and its location in the foreground of the evaluated photographs fundamentally disturbed the scale of the presented landscape in terms of the relationship between the WT with other landscape features [10]. The visual value of a landscape in the background of a picture and its attractiveness were thus eliminated. With slight exaggeration, regarding short distances we can speak about the evaluation of "a wind turbine with surrounding landscape", whereas at long distances it is an evaluation of "a landscape with wind turbines".

We detected more significant changes for all three landscapes, especially between the distances of 1.5 km and 750 m, wherein WTs situated closer to the observer caused a significant decline in visual preferences. In the case of the two visually more valuable landscapes A and B, a similar steep gradient was also detected between the distances 7.5 and 10 km. Otherwise, steep gradients in visual preferences evaluation were indicated at the nearest (for all landscapes) and at the furthest (for the two more attractive landscapes) distance at which the visual impact of WT was perceived. At middle-range distances, the gradient was more gradual.

This finding can correspond with a general ability sensitively to assess outer distances (either close or near) but a lesser ability to detect differences at middle-range distances [18].

Whereas all landscapes with WTs are perceived at close proximity very similarly, the visual impacts at distances further from the observer differ more distinctly. The negative impact of WTs fades out around 10 km distant for landscapes A and B, and in the case of the less-attractive landscape C this occurs already around 5 km. This indicates that WTs situated in landscapes considered to be less attractive reduce visual preferences for these landscapes much less, and this decrease was noted at just half the distance. A WT does not in less-attractive landscapes appear to be such an intrusive element in contrast to its surroundings, and at distances greater than 5 km its visual impact more corresponds with those of other landscape features. The observer can see the WT at this distance, but the visual impact is not determinative for the evaluation of the landscape scene. In contrast, a WT located in an attractive landscape of high aesthetic quality, and one regarded as more natural, acts as an extraneous and contrastive object and visual preferences are reduced by more than twice as much. That negative effect, meanwhile, is still perceived at up to twice the distance.

These findings will be useful for spatial planning of WTs as they can be used to determine circular visibility zones within which the intensity of WTs' visual impact differs and that impact is evaluated more or less profoundly [22]. From this viewpoint, the differentiated evaluation of visually affected landscapes can be defined in two or three visibility zones, as demonstrated in Table 2. Within zones thus identified, it is possible to classify in detail those landscape characteristics which might be negatively affected by WT placement. The effect on natural or cultural qualities of landscape will be more negative in a zone of strong impact than in zones of middle or weak impact. The level of WT impact can hereby be objectified depending on the distance of the evaluated area from the typical observer.

This spatial differentiation of affected landscapes is similarly supported by the work of other authors [22], although their approach to delineating visibility zones is based on subjective albeit expert estimates. In the manner of delineation discussed above, the resulting delineations are determined via quantitative analysis. We should emphasise, however, that the size and design of the WTs may well constitute an important variable. Our experiment involved a WT size (105 m high, 90 m rotor diameter) and type which is among the most frequently erected in Central Europe. Had the data been collected and processed regarding WTs having distinctively different parameters, then the results could have been different. Our specific findings, conclusions and recommendations should therefore be taken and applied with due care and consideration.

4.2. Effect of number of WTs

The score of visual preferences was generally from 1 to 2 points lower in the case of close distance (i.e. 1.5 km) for different numbers of WTs. It can be assumed that this evaluation with increasing distance would further rise, as other studies can affirm [21,36] and would accord with our findings discussed in the previous section. The decrease from 3 to 4 points between the evaluation of 1 WT and 25 WTs for both tested distances (1.5 and 5 km) was roughly the same and substantial. Lower ratings for higher numbers of WTs have also been reported by other authors [8,16,17]. The reason for this lies in the increasing proportion of negatively perceived elements within the landscape. Common natural features and those associated with the cultural landscape are visually stifled due to the WTs' expression, and those features' replacement by unoriginal geometrical objects of such size disrupts the scale of the landscape [29]. With the sole exception of one WT at a distance of 5 km, the evaluation of all WTs at both distances had negative ratings. This shows the tendency usually to assess a landscape negatively if it has WTs present, and this result corresponds with the findings of other authors [3,20,26].

The results of our study reliably confirmed the presumption that an increasing number of WTs reduces visual preferences. This indirect dependency was affirmed regardless of the distance from the observer and separately at two tested distances. The decrease in preferences, however, had a different behaviour at each distance. Although the accretive number of WTs at a distance of 1.5 km reduced scores significantly at the beginning, with further WT additions the dynamic of the score reduction declined and the decrease in score stopped at about 20 WTs (in as much as a presence of 25 WTs was perceived more or less the same). The relative tolerance to increasing numbers higher than 10 WTs might be determined by the observer's weaker ability to recognise individual WT structures but rather to perceive them as a compact group [37]. With respect to WT size and close proximity to the observer, respondents had a diminished ability to distinguish the number of WTs or to perceive the size of the group. The higher numbers of WTs already covered most of the view for the observer of the photograph, and their changing amount was more difficult to detect.

The decrease in visual preferences at a distance of 5 km was in all cases steep, although that decline came to a complete halt between 5 and 10 WTs. Generally, compared to the closer distance, the trend of decreasing preferences at a distance of 5 km indicated the ability of respondents to recognise changing numbers of WTs in larger groups at this distance. The assessment of increasing number of WTs had always a lower score in visual preferences, regardless of the landscape visual quality.

This part of the research did not confirm our presumption that abrupt decreases in preferences for higher number of WTs could be expected due to the cumulative effect, whereby the observer would cease to perceive individual structures but rather see only a visually compact group. Such presumptions have been discussed in some cases involving practical assessment of WTs' visual impact [17,27]. While this trend was not affirmed at the distance of 5 km, in the case of distance 1.5 km the decrease in preferences for higher number of WTs even decelerated and nearly ceased.

4.3. Effect of landscape visual quality

The results from this part of the study indicate a very interesting phenomenon not previously reported in any other study. Three tested landscapes without WTs were ranked with statistical evidence in order from the most to least attractive (A – B – C) based on visually relevant attributes of the landscapes. In the case of assessing the same landscapes with the presence of various numbers of WTs (1–25), this rank order of evaluation was reversed. The visual preferences for the most attractive landscape A were the most reduced after one or more WTs were added to the photograph (decrease from +5.52 to −2.42), whereas the diminution

Table 2
Indicative delineation of visibility zones to determine the level of visual impact on landscape for wind turbine (WT) planning using circular diameter with the central point in the position of assessed WTs. The visibility zones are proposed for WTs with hub height 105 m and rotor diameter of 90 m.

Landscapes of	Landscapes of high aesthetic quality (km)	Landscapes of low aesthetic quality (km)
Strong impact	0–1.5	0–1.5
Middle impact	1.5–7.5	
Low impact	7.5–10	1.5–5

for the least attractive landscape C after adding WTs was the lowest (decrease from +1.93 to −2.00). Furthermore, this finding entailed not just the highest relative decrease in landscape A's evaluation, but a decrease from absolutely highest rating to absolutely lowest.

Apparently, respondents evaluated negatively the contrast of WTs with the most attractive and natural landscape A. This contrast or unsuitability of WTs location in such landscape outweighed even the positive landscape attributes in the respondents' assessments and they tended to penalise such contrastive combination by giving it the absolute lowest rating. The effect of different landscape types was demonstrated especially at the close distance of 1.5 km, where the negative impact occurred especially in evaluating the most attractive landscape A. On the contrary, the impact at this distance was smallest in preferences for the least visually attractive landscape C. At this distance, the evaluation of three edited landscapes (with WTs) simulated the overall evaluation of landscapes with added WTs, meaning without difference according to distances. At a distance of 5 km, the distinctions between the assessed landscapes with added WTs were negligible. At this distance, further increasing the number of WTs in landscape C had relatively the smallest negative impact on its assessment.

Taken as a whole, these findings underscore the role of landscape type in the process of evaluating WTs' visual impact. This has been confirmed by other authors [9,19,20,26,27], who emphasise the role of landscape in assessing the placement of WTs. None of the cited papers, however, mention such a dramatic decrease in the relative and, in particular, the absolute scores for visual preferences in a landscape of high aesthetic quality. In assessing WTs' visual impact, therefore, it is important to evaluate carefully the visual quality of the landscape itself. In considering the suitability of landscapes for possible placement of WTs, it is necessary to protect especially the visually attractive and natural landscapes whose visual qualities could be the most degraded. Conversely, it makes sense to concentrate WTs in landscapes with low visual qualities and possibly in landscapes which already are influenced by other objects bearing negative visual impacts [19,27].

5. Conclusion

This study's findings and approach, in combination with earlier, case-type studies and their findings, should stimulate new thinking and approaches in assessing WTs and planning their placement while focusing attention upon WT number, WT distance from a typical observation point, and the visual quality of a landscape. All these variables, and including their interactions, had highly significant effects on the evaluation of a landscape's visual quality. Number of WTs had the greatest impact, while the observer's distance from a WT had a smaller effect and landscape type had the smallest effect of all. The results confirmed the importance of landscape's aesthetic value and that WTs will face greater opposition in natural and visually attractive landscapes. The most attractive landscape with the most positive score initially was evaluated with the absolutely most negative ratings after WTs were added. This finding strongly suggests that placement of WTs in landscapes with natural character and high aesthetic value should be avoided. The landscape qualities – including both natural and cultural attributes – should be assessed before any WT placement and in the very earliest stage of any contemplated WT development. In the planning process, landscape visual quality should be evaluated and landscapes of high aesthetic value should be protected against development on such scale as constituted by wind farm projects.

Furthermore, we have determined the interaction between landscape visual quality and distance from the observer and found that distance thresholds varied according to landscape attractiveness. The visual impact of WTs in landscapes with high aesthetic values disappeared at a distance of around 10 km. In less-attractive landscapes with stronger human influences, this breakpoint was at around half that distance (about 5 km). The close proximity of WTs to any type of landscape was considered to be a very negative intrusion, regardless of the visual attractiveness of the landscape itself. Consequently, we have proposed the designation of visibility zones to objectify the intensity of WTs' visual impact on the landscape. The visibility zones should be applied in the planning process according to landscape type in order to mitigate the visual impact of WTs as much as possible.

An interesting finding was established for the interaction between the number of WTs and distance from the observer. The perception of WTs in a group was different at the close distance of 1.5 km compared to the middle-range distance of 5 km. The landscape of high aesthetic value was significantly more negatively influenced by the number of turbines at a close distance. Although cumulative effect was not significantly proven in this study, a rising number of WTs was determined to be perceived increasingly negatively for all tested landscapes. The dynamic of that diminution in score was lower, however, for the least attractive landscape which was already characterised by strong human impact and decreased naturalness.

The results of this study can make a substantial contribution to reducing negative visual impact in the WT planning process and thus to achieving higher public acceptance of these structures. The identified thresholds for distance from the observer and number of WTs may help to improve the methods for assessing WT impact and elucidate the reasons for why wind farm projects are rejected. To achieve higher public support, the placement of WTs must respect the aesthetic qualities of the landscape with consideration for its general character, natural and cultural attributes, observation points, and other factors. Towards this end, public officials may incorporate into their decision-making process visual impact assessment of renewable energy schemes and WTs planning that incorporate all these physical attributes.

Acknowledgements

This study was supported by Grant Nos. 20134279 and 20144220 from the Internal Grant Agency of the Faculty of Environmental Sciences at Czech University of Life Sciences in Prague, Czech Republic and by Grant No. LH11069 from the Ministry of Education, Youth and Sports of the Czech Republic.

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