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The application of GIS and 3D graphic software to visual impact assessment of wind turbines

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ABSTRACT

Visibility of wind turbines is one of the most subjective factors influencing the decision on the potential location to build wind turbines. The spatial extent of the visual impact of wind turbines usually covers a wide area. The paper proposes a new method for visual impact assessment of wind turbines. The proposed method uses GIS tools and 3D graphic software for developing three-dimensional models and computer animations. The developed method was verified in the field. The usefulness of this method is presented on the example of the Poznań Metropolis in Poland, where construction of wind turbines is considered. The analyzes related to visual assessment of the effect of wind turbines with a height of 150 m above ground should be performed over a distance reduced to 12 km. Visibility range of wind turbines depends on the position of the observer in relation to the wind turbine. For longitudinal, diagonal and frontal views the visual impact is limited to 4, 10 and 12 km, respectively.

The results obtained using the method proposed were compared with those provided by the other methods used to assess the visibility of wind turbines. As a conclusion, the advantages of this method in favor of its popularization were described.

1. Introduction

Most governments worldwide actively promote the use of renewable methods of electricity generation. Wind farms have developed rapidly in recent years and have been commonly recognized to be a clean and environmentally friendly source of renewable energy. Besides the well-known benefits of renewable energy sources, their use is related to some problems. The production of energy from renewable sources requires the use of larger areas when compared with those needed by conventional sources. Consequently there are potential environmental impacts of installation and operation of wind turbines [1]. The disadvantages of wind farms are noise pollution, shadow flickering, aesthetic integration into the landscape and other impacts on humans and ecosystems, including the killing of wildlife, especially birds and bats [2].

The most contentious issue associated with wind farms is the visual impact. The visual impact of wind farms on the landscape is much greater than that of conventional sources. Usually the focus of visual impact assessments is on the public landscape: views seen from parks, recreation areas, publicly accessible trails, water bodies, highways or roads (especially designated scenic highways), scenic overlooks, publicly accessible historic sites, and village or town centers [3]. In the past decade the interest in evaluating the visual impact of wind farms on cultural heritage, cultural landscape [4,5] and tourism landscape potential has increased [6].

The dominant subject in literature in the field has been the visual impact of wind turbines [7]. The visual effect of wind turbines depends on the distances from the viewer [8,9]. The distance, at which a wind turbine is visible, is limited by its height; an outer radius of 150 times the total turbine height, as derived from studies such as [11]. In more detail Shang and Bishop [11] have defined the minimum resolvable size of an object at various distances. Visual impact assessments of the wind turbines in Europe has been conducted since the early nineties of the last century. The first reports of the European Commission from 1995 on the visual analysis of low wind turbines with a height of about 45 m showed that the maximum range of visibility is 20 km. Thomas, on the basis of a study conducted in Wales for wind turbines with a height of 41–45 m has shown that the maximum range of visibility analysis of turbines should be limited to 15 km and next he has made adjustments to 20 km [38].

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Sinclair on the basis of analysis of wind turbines with heights from 52 to 95 has proposed slightly different limits to be adopted in the visibility analysis of wind turbines. For the lowest turbines with a height of 52–55 m he suggested that the analysis of their visibility should be performed within 20 km and for the turbines with a height of 70 and 95 m to 25 and 30 km respectively [38].

At the turn of the century the higher and higher wind turbines were built and the extent of their visibility according to Bishop exceed 30 km. However, Bishop [37] believes that above 20 km visibility of the turbines is very limited and its impact is very low.

Miller et al. [36] has suggested however, that the maximum visual analysis range of wind turbines should reach up to 35 km. On the other hand, Vissering [3] argues that the visual analysis of high wind turbines should extend to 40 km distance.

Molina-Ruiz et al. [21] have proposed a method to quantify the maximum visible distance for a tall linear object (suitable for analysis of wind turbines). The calculations presented by these authors [21] for a 50 m high wind turbine suggest that the range of its visibility is of about 30 km. The methodology for assessment of the visibility of wind turbines proposed by Molina-Ruiz et al. [21] does not take into account the obstacles between the wind turbine and the observer which can make significant influence on visual impact level as shown in this paper.

The visibility depends on complex interactions of a variety of factors [12]. The degree of impact is diminished by factors such as the nature of the background and the landscape between the viewer and the turbines, lighting, atmospheric conditions and moving or stationary blades [8]. The sensitivity of people to the placement of wind turbines in landscapes of high aesthetic quality is greater [9,13].

Shang and Bishop [11] have developed a systematic procedure for the assessment of three visual thresholds detection, recognition and visual impact. The thresholds were obtained through controlled slide-viewing tests using computer simulated images with modified visual attributes: size, contrast, object type and landscape type.

There are many studies on the wind farms visual impact on landscape including various methods for measuring visual impact and visualization [15,16]. Several methodologies have been developed for the visual impact assessment of wind farms [17]. In recent years, Geographic Information System (GIS) has become a major tool used for three-dimensional analysis [18]. Viewshed analysis in GIS environment has become widely accepted for visual impact assessment of wind turbines [19,20]. Molina-Ruiz et al. [21], Rodrigues et al. [17], Minelli et al. [22] have used the principle of line-of-sight to assess the visual impact of wind farms. Minelli et al. [22] on the basis of this principle have proposed the non-dimensional visual impact index (NI). The NI index is calculated as the ratio of the perceived area of wind turbine and the area of the field of view. To evaluate the NI index Minelli et al. [22] have developed a Python script r.wind.sun working in GRASS GIS environment. The advantage of the method developed by Minelli et al. [22] is that it takes into account the effects of the real 3D distance between the observer and the object and the distortion of size and shape caused by the human eye in concurrence with the presence of a non-planar terrain morphology. Molina-Ruiz et al. [21] have developed a methodology to determine and predict the visual impact based on the visual scape analysis and taking into account the observer visual acuity.

Nowadays GIS-assisted multi-criteria evaluation are used to minimize the environmental impact of the wind farms development, e.g. Watson and Hudson [23]. Based on visibility maps, different scenarios can be constructed, presented and objectively compared. Furthermore, the visibility analysis supplies an instrument that can objectively evaluate the effect of landscape design plans minimizing the visual impact to the greatest possible extent [24]. These techniques can be used for analysis and decision-making in environmental administration, and are useful to planners and designers attempting to choose locations of new man made facilities [18]. Mekonnen and Gorsevski [25] have designed a prototype that integrates GIS and decision-making tools to involve different stakeholders and the public for solving complex planning wind farms problems and building consensus. Other GIS-based studies focused on finding suitable areas in terms of visual impacts and assessed wind energy potential [26].

To quantify potential visual impacts of wind farms, digital landscape visualization techniques are used. For the above reasons, to assess the real impact of wind farms on the landscape, different visualization tools such as digital image processing and photo-realistic animations are used [27,28]. To assess the aesthetic impact on the landscape caused by wind farm, a specific indicator has been defined by Torres et al. [29]. The indicator combines measures of visibility, color, fractality and continuity which can be taken from photographs [29].

In the last few years, the technological advances in digital landscape visualization tools and techniques allow the use of digital 3D visualizations [30]. The software allows realistic 3D visualization of animated wind farms with high level of realism based on GIS-data [31]. In last few years, combined use of quantitative indicators and software for 3D simulations has been suggested for practical examination of the visual impact [32].

In this paper, we propose a new method to quantify visual impact assessment of wind turbines. The method proposed is based on standard GIS tools, Digital Surface Model (DSM) and rendered images of wind turbine prepared in 3D graphic software – Blender. It takes into account the spatial extent with visibility range, angle of view and wind direction.

The study permitted determination of the maximum spatial extent of the visual impact of a single wind turbine depending on the position of the observer. The verification of the method assumptions was made on the basis of existing turbine images and simulations in 3D graphic software Blender. The method was tested on the vicinity of the city of Poznań in Poland, where the localization of new wind turbines is being considered.

2. Methodology

The visual impact assessment of a wind turbine was based on Digital Surface Model (DSM). To assess the visual impact of wind turbines is preferable to use the existing ready-made Digital Surface Model (DSM) resources available in the national database. These models can be used directly in the analyzes without the need for additional treatment. It is also possible to use Digital Elevation Models (DEM) for analysis, which, however, should be complemented by surface objects like buildings, forests, etc. such a model was used in this study. Models should be used in grid format.

The free of charge DEM data of grid intervals not greater than 100 m were used in this study. DSM preparation based on DEM requires the use of standard GIS tools to incorporate surface objects along with the determination of their height. In a simplified way, the height of buildings can be determined on the basis of the number of storeys. The type of the source materials used in DSM construction and its spatial resolution influence the outcome of the analysis. It is recommended to use the most accurate DSM available.

2.1. Spatial extent and wind turbine visibility range

The visual impact assessment methodology was demonstrated for a typical wind turbine with a height of 150 m. The visibility analysis of the wind turbine was made using ArcGIS 10.1. Spatial

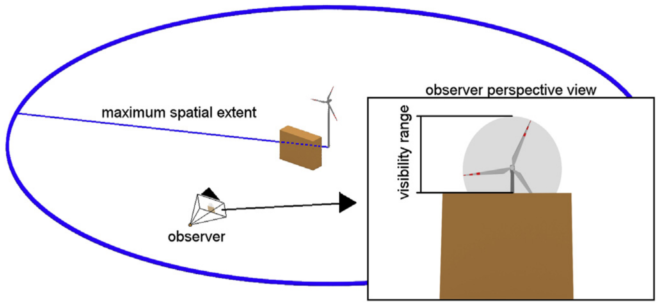

Fig. 1. Spatial extent and visibility range scheme.

Analyst extension and a Viewshed tool was used. The Earth curvature correction factor was taken into account.

Spatial extent is defined as the area from which the wind turbine is visible. Visibility range is defined as the height of the visible part of wind turbine after taking into account the obstacles between the wind turbine and the observer (Fig. 1).

In order to determine the range of the wind turbine visibility, analysis was carried out in several repetitions, assuming that with each step, the height of the turbine is lowered by 10 m. The results of each subsequent analysis is a raster, in which the value of 0 – indicates a lack of visibility and 1 – visibility of wind turbine. In order to determine the range of wind turbine visibility from each location, 15 subsequent rasters were summarized using raster calculator tool available in the ArcGIS. As a result of such a procedure the output raster was obtained in which each cell was assigned a value from 0 to 15. When the value of the cell is 15, this means that from this location the whole wind turbine is visible and when a cell value is 0, it means that the turbine is not visible. The proposed method allows precise determination of the visibility of a wind turbine, in accordance with the scheme shown in Fig. 2. The cell values determine how many 10 m segments (from the top) are visible to the observer.

2.2. The method for limiting the spatial extent of wind turbine visibility for different angles of views

Determination of the maximum spatial extent of the visual impact of the wind turbine was conducted in the Blender 2.74 software. Blender is a professional free and open-source 3D computer graphics software used for creating visual effects and interactive 3D applications. Blender is a fully integrated 3D content creation suite, offering a broad range of essential tools, including modeling, animation, many types of simulations. In order to determine the maximum extent of visibility of a wind turbine a three-dimensional model was built (Fig. 3).

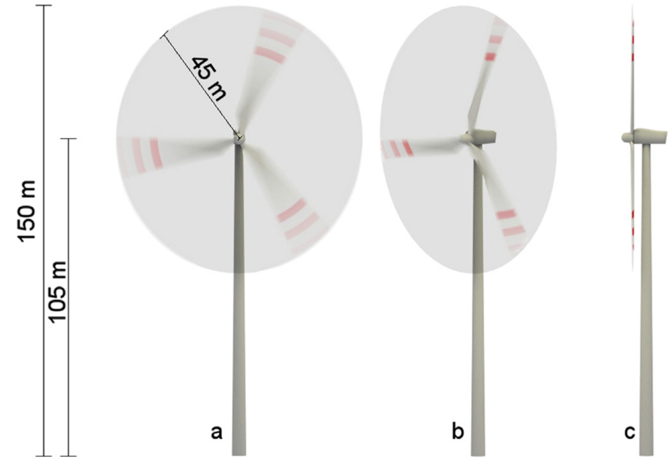

Fig. 3. Wind turbine models considered in the procedure of impact on landscape evaluation; a – frontal, b – diagonal and c – longitudinal view.

A real-scale wind turbine model and a virtual camera in the Blender environment allowed determination of wind turbine visibility from any location. Images were rendered with resolution of 1920 × 1080 by a virtual camera set in front of the wind turbine at a known distance. Virtual Blender camera was set to 50 mm focal length and sensor full frame size. The use of these attributes is recommended in visualization and photomontage [40] and it has been conventionally used as similar to the human eye. Verification of this correspondence was based on the real photographs of the existing wind turbines located in the immediate vicinity of Poznań Metropolis. Photographs were taken at specific locations taking into account the distance of the observer to the wind turbine with a Canon D50 camera with an APS-c and for 17–70 mm lens set to 31 mm equivalent focal length equal to a full frame sensor size and lens of 50 mm. Fig. 4 shows that the modeled wind turbine (black) is equal to the real one, which means that assumptions were correct and Blender software is suitable for visibility analysis by simulating real camera.

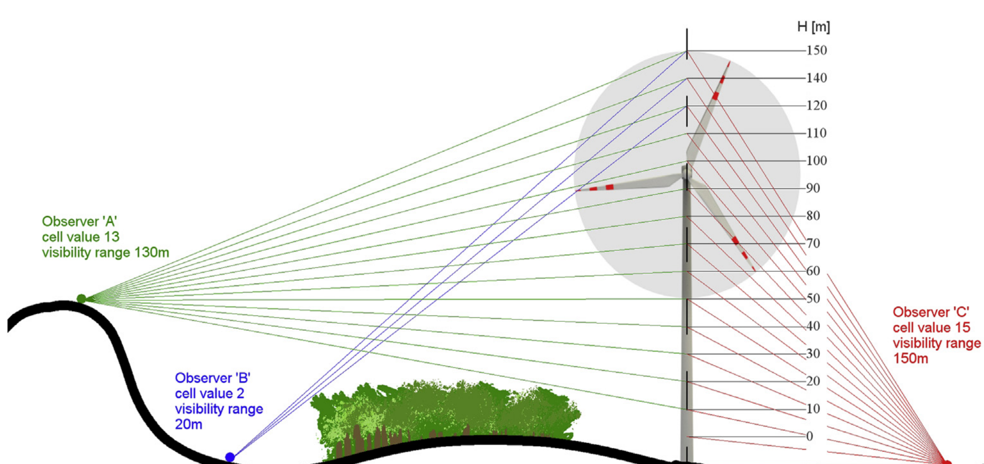

Fig. 2. Schematic presentation of the procedure used for the wind turbine visibility range determination.

Fig. 4. Comparison of the modeled and existing wind turbine.

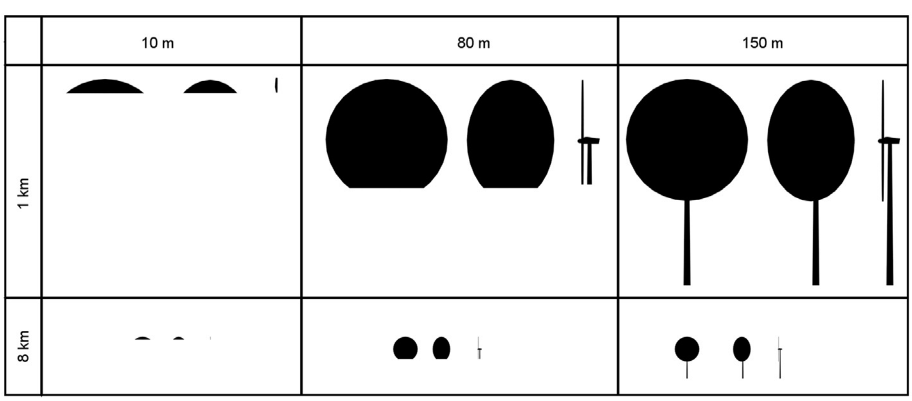

Fig. 5. The visible size of a wind turbine of 10, 80 and 150 m from the top, as seen from the distance of 1 and 8 km.

The aim of the simulations was to determine how the visibility of the wind turbine decreases with distance. In order to achieve this, the rendered images of wind turbine taken at different distances were analyzed. During the simulation it was assumed that the terrain is flat and free of any obstacles. It was also assumed that the wind turbine is black while the other elements of the landscape are white. Wingspan was analyzed as a circle described on the rotor, as a simplification of the working turbine.

Fig. 5 shows an exemplary scheme for determination of the visibility of a turbine for the visibility range of 10, 80 and 150 m and from the observer distance of 1 and 8 km.

In the first simulation, the images were rendered for the only one 10-m segment visible from the top from distance from 1 km to 20 km with interval of 1 km. Then, simulations were repeated 14 times, assuming that in each subsequent step, one 10-m segment below is added. Simulations were performed assuming the frontal,

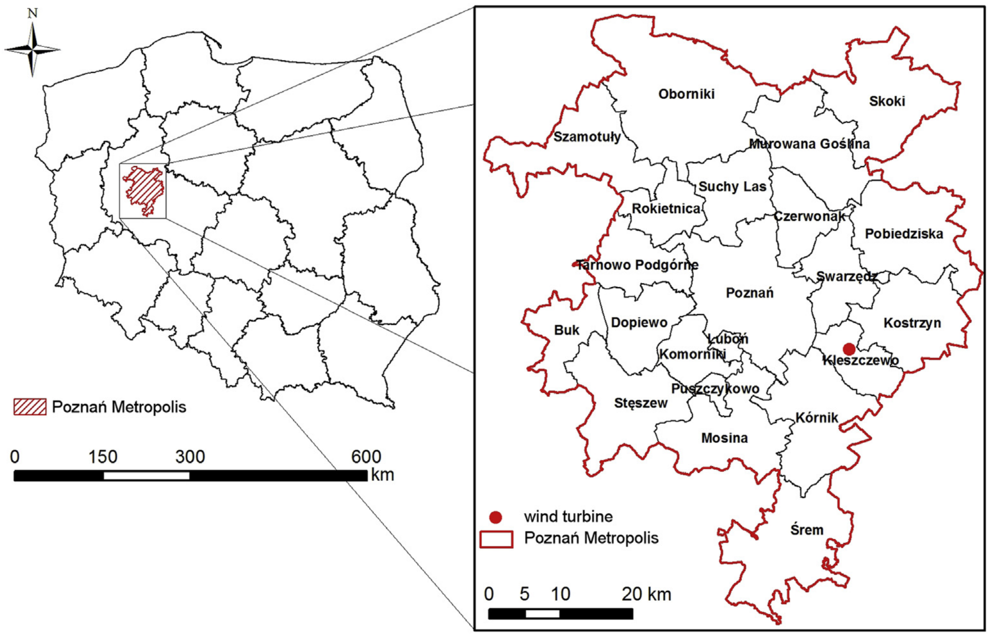

Fig. 6. Study site location.

diagonal and longitudinal position of the turbine. They gave a total of 900 rendered images. Next, the percentage area of the wind turbine with respect to the total field of view was calculated in every single rendered image. It allowed the assessment of the visual impact of a wind turbine depending on its distance and visibility range. The analysis threshold does not mean that the wind turbine cannot be seen, however the area of the wind turbine with respect to the total field of view is very small, and should not be the part of the visual impact assessment.

The visual impact assessment was made taking into regard the direction of the wind and the frequencies of winds from a given direction. For the major wind directions E or W and S or N and NE or SW and NW or SE the maps were made, presenting the percentage area of the wind turbine with respect to the total field of view, taking into account the distance of the observer and the extend of its visibility.

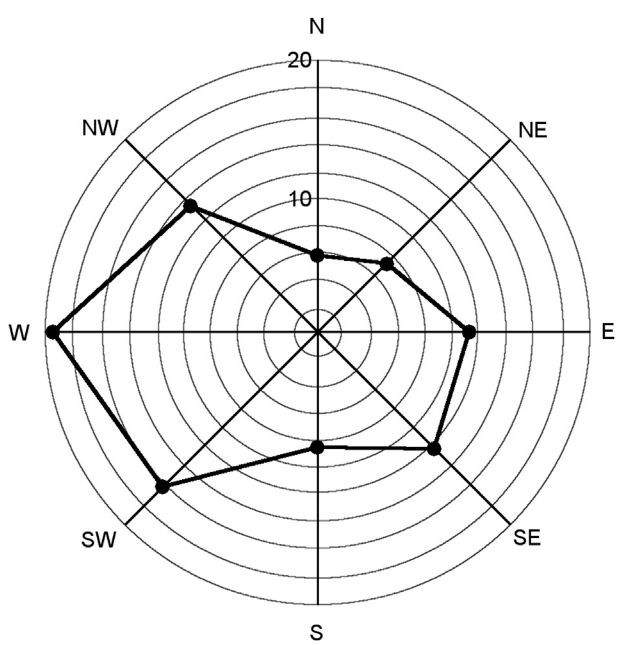

Fig. 7. Dominant wind directions in Poznań and its vicinity.

3. Results – case study

3.1. Study site location

Poznań Metropolis (Fig. 6) is located in the western part of Poland and covers the area of about 3081 km^2. The altitudes in this area range from 42.35 m to 159.22 m with an average height of 96.21 m a. s. l. The lowest areas are located within the Warta River valley, which cuts the metropolis area into two parts: east and west. The highest areas are situated in eastern and southeastern parts. Poznań Metropolis occupies 10% of Wielkopolska region, inhabited by more than 1 million people representing 29% of the total inhabitants of the Wielkopolska region. Poznań with suburban communities forms a monocentric settlement, with the center of at the city of Poznań, surrounded by the 21 communes. In the National Spatial Development Concept 2030 [33], the city of Poznań is defined as one of 9 metropolitan centers in Poland. In the area of Poznań and its vicinity it is planned to increase the share of energy produced from renewable sources. For this purpose, analyzes were performed to indicate the possible localizations of wind power facilities, based on established criteria [34]. The study site covered the area within which the possibility of building wind turbine towers is considered.

The study area is dominated by the winds from the west. The winds from the west or east have been noted on 34% of days in the year. The winds from the other directions N or S, and NE or SW and NW or SE occur with a smaller frequency of 16%, 24% and 26%, respectively (Fig. 7).

3.2. Digital surface model

In the first stage of work for the whole area of Poznań and its vicinity, a Digital Elevation Model (DEM) was constructed on the

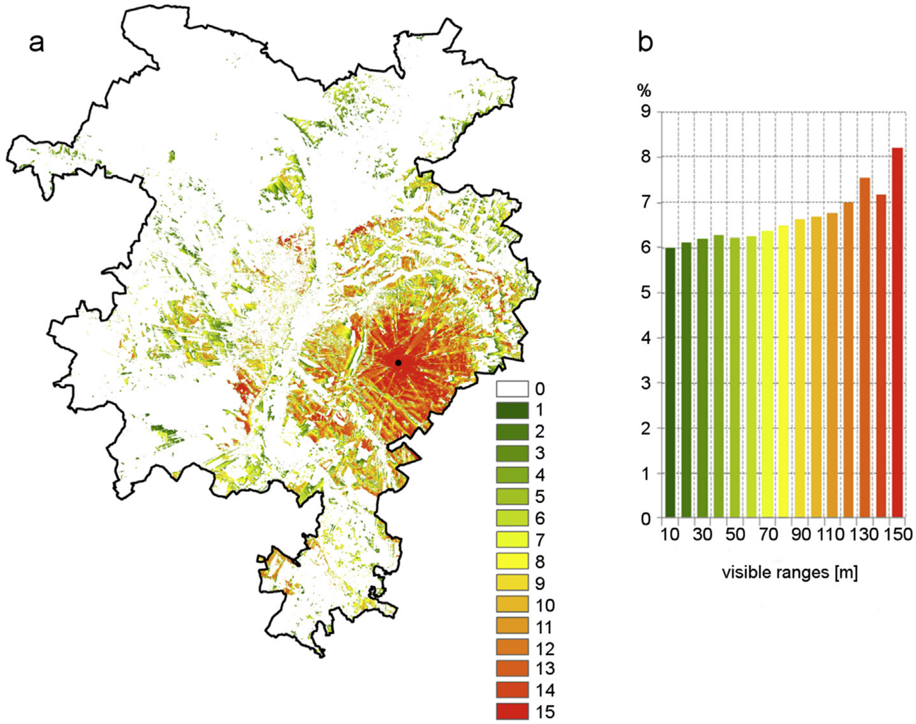

Fig. 8. Visibility analysis of wind turbine, a) spatial extent and range of visibility, b) percentage share of visible ranges.

basis of the data obtained from the Head Office of Geodesy and Cartography. DEM was developed using a set of points with interval of at least 100 m, with ArcGIS Software (ESRI) with a 3D Analyst extension, in the GRID form with spatial resolution of 10 m. DEM was supplemented with elements of land cover. The structure of land cover was determined on the basis of Topographic Objects Database (TOD). TOD is the reference database in Poland, which contains among others updated information on the buildings and it is made in a nominal scale of 1:10 000. Buildings height was determined in a simplified way. The number of storeys in a building was multiplied by the height of storeys, which was adopted at the level of 3 m. Height of natural land cover types such as forests and afforestations was determined on the basis of the information provided by the Data Bank on Forest General Directorate of State Forests in Poland.

3.3. Visibility range analysis

Visibility analysis was carried out for one of selected locations (Fig. 6). It was assumed that the analysis would be conducted for

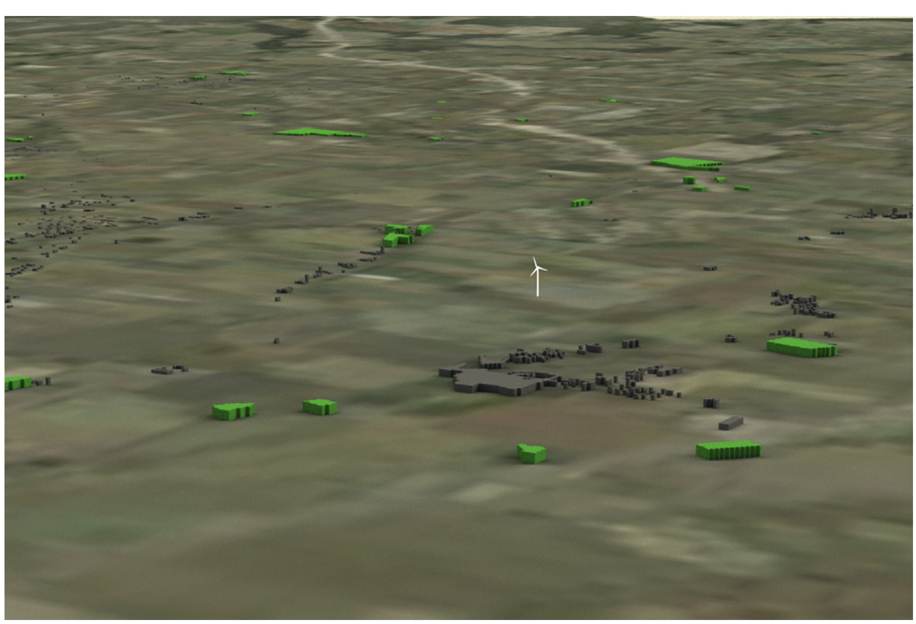

Fig. 9. A wind turbine against a model of Poznań and its suburban areas made in Blender software.

the turbine type V90 – 2 MW by Vestas company. The tower height is 105 and wingspan radius is 45 m.

The spatial extent of and the range of the wind turbine that would be visible were determined. The analysis showed that the theoretical extent of the wind turbine visibility is very high. The extent of the analysis is limited by the area of DSM. Visibility range of wind turbine varied from 10 to 150 m (Fig. 8).

Viewshed methods allowing for visibility analysis are based on a digital analysis of the obstacles between the analyzed entity and the location of the observer. This approach can suggest an area of visibility that exceeds the possibilities of the human eye. It was confirmed by the 3D simulations made in Blender software, in which a model of Poznań and its vicinity was constructed. Digital Elevation Model made in ArcGIS was imported into Blender environment. Then GIS shapefiles of the location of buildings, forests and afforestations of the studied area were added. Addition of GIS layers to the Blender software was possible thanks to the Bender GIS addon (source: https://github.com/domlysz/BlenderGIS). The shapefiles attribute table contained elevation and height values, of individual objects which were used to develop simplified 3D models of buildings and forests. The model of wind turbine was placed in the planned location (Fig. 9).

According to the analyses in the Blender environment, the actual spatial visibility extent of a turbine was smaller than that calculated with the use of Viewshed tool. Fig. 10 shows an example of analysis made using ArcGIS and Blender software. The observer, at about 22 km away from the wind turbine is located in the zone of visibility of the whole wind turbine (cell value 15 – red color) (in the web version) (Fig. 10a). The observer perspective view (Fig. 10b) does not indicate that the wind turbine is visible (at this rendering resolution and size of reproduction). The render made at 20× zoom shows that there are no physical barriers between the wind turbine and the observer, which shows the accuracy of the method of visibility range calculation (Fig. 10c).

3.4. Visibility extent analysis

On the basis of analysis of rendered images, the percentage area of the wind turbine with respect to the total field of view was calculated. For the frontal, diagonal and longitudinal positions for which the turbine occupied the area smaller than 0.1%, the photorealistic visualizations were performed in the program Blender. On the basis of the analyses, it was concluded that the visibility of the turbine is very limited and its impact is very low when it occupies the area less than 0.02% relative to the total analyzed image. Outside this extent the wind turbine could still be visible but its percentage share in the field of view is small and its visual impact is insignificant. The spatial extent of the analysis (visual impact threshold) in accordance with the developed methodology, was reduced for frontal, diagonal and longitudinal position to 12, 10 and 4 km, respectively (Table 1).

The obtained results showed that the range is gradually

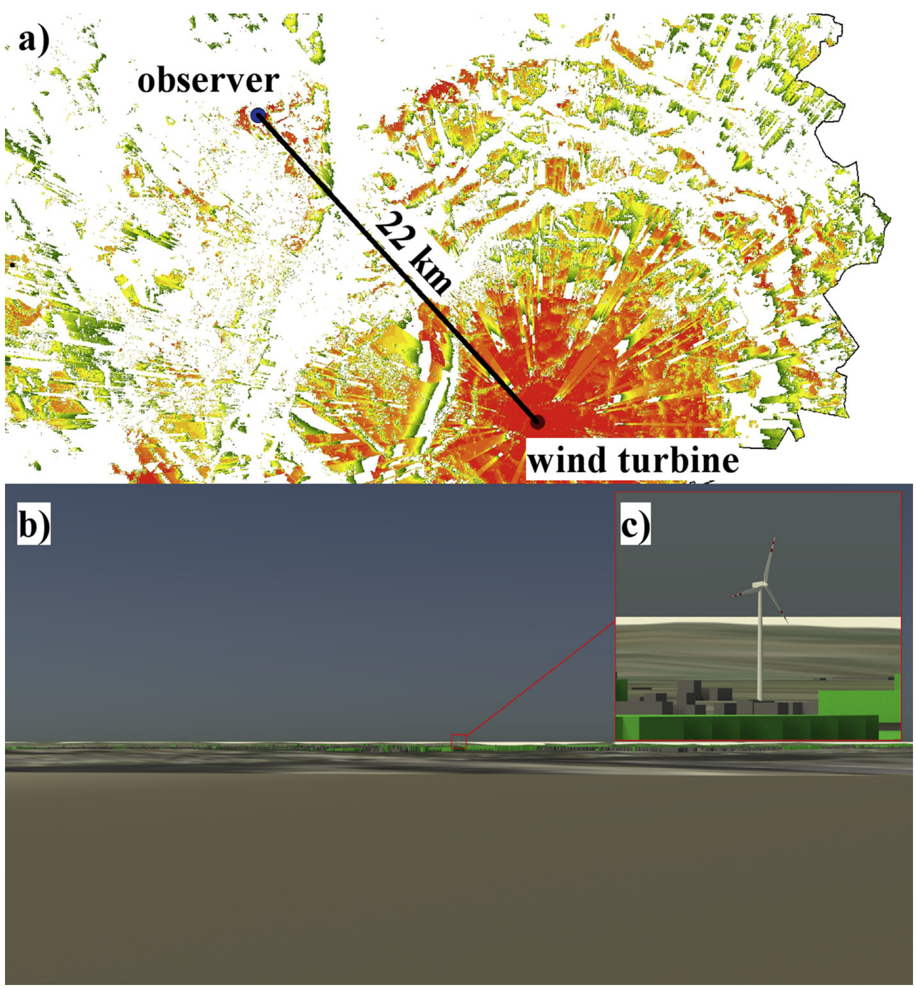

Fig. 10. a) Location of observer and wind turbine, b) observer perspective view, c) 20× zoom on the wind turbine.

Table 1
Percentage area of the wind turbine on rendered images.

Distance [km]	Visibility range [m]														
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
Frontal															
1	0.166	0.413	0.705	1.020	1.354	1.667	1.964	2.198	2.327	2.346	2.363	2.382	2.401	2.421	2.442
2	0.044	0.109	0.186	0.269	0.353	0.435	0.508	0.568	0.600	0.605	0.611	0.616	0.622	0.627	0.633
3	0.021	0.049	0.086	0.122	0.159	0.198	0.230	0.257	0.272	0.275	0.277	0.280	0.283	0.286	0.288
4		0.029	0.048	0.069	0.091	0.112	0.131	0.146	0.155	0.157	0.158	0.159	0.161	0.162	0.164
5			0.033	0.045	0.060	0.074	0.085	0.096	0.101	0.102	0.103	0.104	0.105	0.106	0.107
6			0.023	0.033	0.042	0.052	0.061	0.067	0.071	0.071	0.072	0.073	0.074	0.076	0.076
7				0.025	0.032	0.039	0.045	0.050	0.052	0.053	0.053	0.054	0.055	0.056	0.057
8					0.025	0.029	0.035	0.038	0.040	0.041	0.041	0.041	0.042	0.042	0.043
9					0.020	0.024	0.028	0.031	0.032	0.033	0.033	0.033	0.034	0.034	0.034
10							0.022	0.025	0.027	0.027	0.027	0.028	0.028	0.028	0.028
11								0.021	0.022	0.023	0.023	0.023	0.023	0.024	0.024
12														0.020	0.020
Diagonal															
1	0.104	0.277	0.492	0.718	0.950	1.184	1.398	1.568	1.667	1.683	1.701	1.719	1.738	1.759	1.780
2	0.030	0.077	0.132	0.192	0.253	0.310	0.363	0.408	0.433	0.438	0.443	0.447	0.453	0.458	0.464
3		0.035	0.061	0.087	0.114	0.142	0.165	0.185	0.196	0.198	0.201	0.203	0.206	0.209	0.211
4		0.020	0.035	0.050	0.066	0.081	0.094	0.106	0.113	0.114	0.115	0.117	0.119	0.120	0.122
5			0.023	0.032	0.043	0.053	0.061	0.069	0.073	0.074	0.075	0.076	0.077	0.078	0.079
6				0.024	0.030	0.038	0.044	0.048	0.052	0.052	0.053	0.054	0.055	0.056	0.057
7						0.028	0.033	0.036	0.038	0.039	0.039	0.040	0.041	0.041	0.042
8						0.022	0.026	0.028	0.030	0.030	0.031	0.031	0.032	0.032	0.033
9							0.020	0.023	0.024	0.024	0.025	0.025	0.026	0.026	0.027
10										0.020	0.020	0.021	0.021	0.022	0.022
Longitudinal															
1			0.030	0.041	0.079	0.104	0.129	0.133	0.157	0.176	0.194	0.212	0.232	0.254	0.275
2					0.021	0.027	0.034	0.040	0.047	0.052	0.057	0.062	0.068	0.073	0.079
3								0.021	0.025	0.027	0.029	0.032	0.034	0.036	0.039
4												0.021	0.022	0.024	0.026

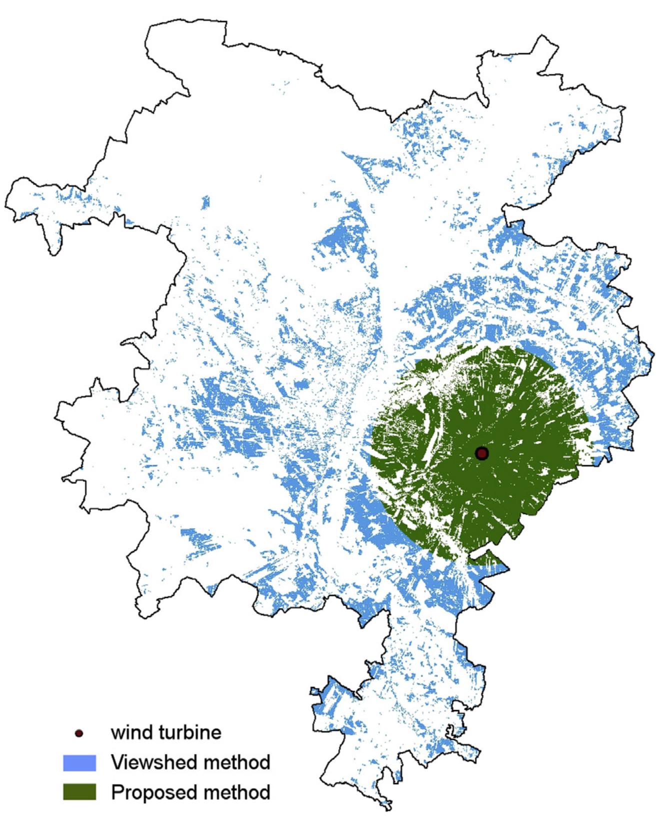

Fig. 11. Differential map illustrating the differences between the results provided by the method based on Viewshed tool and the method proposed in this study.

decreased. It follows not only from the distance of the observer from the turbine but also from angle of view with respect to the turbine and the turbine's visible range. The methodology proposed allowed a reduction in the extent of analysis in relation to that in the standard GIS method. The maximum area of the visual impact assessment of a wind turbine based on Viewshed tool reaches 675 km^2. Assuming the results obtained in this paper, the analysis can be limited to 12 km, so that the area of detail analysis is 293.8 km^2 (Fig. 11).

The percentage area of the wind turbine with respect to the total field of view was calculated for the dominant wind directions. On the basis of the calculations, maps were made in which the potential impact of the turbine on the surrounding terrain was illustrated (Fig. 12). According to the maps, at a distance over 4 km the turbine area share in the field of view is lower than 0.164%, 0.122% and 0.026% for the frontal, diagonal and longitudinal position, respectively.

The proposed combined use of GIS and 3D graphic permits easy presentation of results. The GIS software permits making maps of potential impact extent and intensity of the turbine impact. The 3d graphic software enables preparation of realistic renders and animations for any localization. A still from each animation for 5 exemplary localizations are presented in Fig. 13.

4. Discussion

The analyzes conducted in this paper showed that the maximum distance of visual impact assessment of 150 m high wind turbine should be limited to 12 km. The proposed analysis threshold is basically smaller than reported in literature according to which the analyses of visibility were performed from 20 to 40 km [3,21,36–38]. Hurtado et al. [14] have suggested that for the observer located at a distance greater than 6 km from a wind turbine its visual impact is minimal and the wind turbine should be

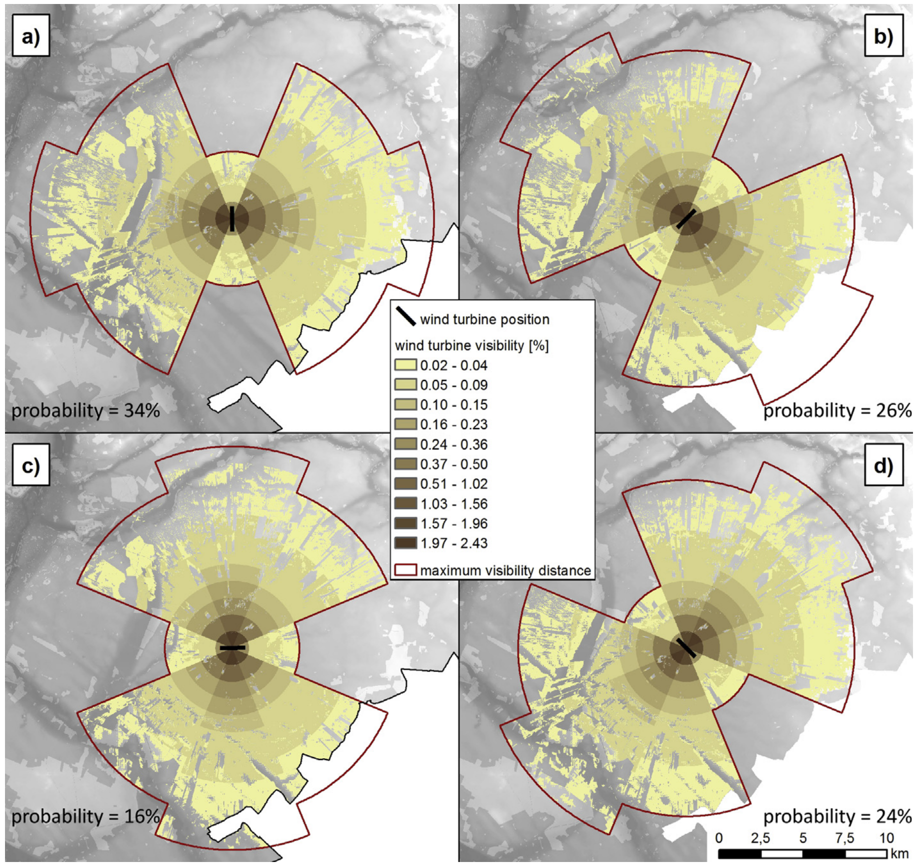

Fig. 12. The percentage of wind turbine in total field of view for different wind direction a) W/E, b) NW/SE, c) N/S d) NE/SW.

considered as part of the background landscape. Betakova et al. [10] have determined the interaction between landscape visual quality and the distance from the observer and found that distance thresholds varied according to landscape attractiveness. The visual impact of wind turbines 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 relatively high level of acceptance of these structures in unattractive landscapes has been observed [13]. Results of this paper however have shown that these assumptions are insufficient for 150 m tall wind turbines. The analyses performed have shown that the maximum visual threshold distance is greater and equals 12 km.

Shang and Bishop [11] have established that the minimum object size that a person with a normal visual acuity is able to recognize is 25 arc minute^2, which corresponds to 0.000649% according to the method proposed in this paper and based on renders of resolution of 1920 $\times$ 1080. This value, to be exact 25.9 arc minute^2 $=$ 0.000675%, was obtained in the render made from the distance of 101.5 km for the frontal view. In the render taken at the distance of 102 km, the turbine was no longer detected.

The results in arcmin^2 are relatively difficult for direct interpretation, so in this paper we proposed quantification of the visibility impact as the percentage area of the wind turbine with respect to the total field of view. Many researchers have suggested that the visibility threshold of a wind turbine depends on the angle of view. The greatest visual impact is in front view of the turbine and the lowest is at a longitudinal angle of view. Hurtado et al. [14] have introduced the correction factors related to the observers position. He proposed three values for the frontal, diagonal and longitudinal angle of view equal to 1, 0.5 and 0.2, respectively. Analysis conducted in this papers shows that values for the diagonal and longitudinal view should be increased to 0.7 and 0.4.

The most frequently used methods for visual impact assessment of wind turbines include the visual impact threshold determination [11], Spanish method [14] and its updated version [35], the objective aesthetic impact method [29] and methods of determination the impact zone [17], 3D simulations [21] and Visual impacts index [22]. Visual impact assessment reported by Torres et al. [29] has been made on the basis of four criteria: visibility, color, fractality and continuity. Especially important is the visibility factor which can take a value from 0 to 1. This allows easy interpretation of the results. A slightly different approach to the visual analysis has been applied by Rodrigues et al. [17]. His method allows a calculation of the maximum visible distance assuming that the visible area for a renewable technology devices is a rectangle with an area equal to the device width multiplied by the device height. Rodrigues et al. [17] have used a perception index for visual analysis over the area of 10 km radius. The proposed procedure can raise some difficulties. The calculated values of perception index may vary over a large range of values from 0.0001 to 10. The visual impact index proposed by Minelli et al. [22], similarly to the perception index introduced by Rodrigues et al. [17] is defined as the ratio of the object area to the entire field of view. In the method proposed, the results of analysis are presented in a similar way but additionally takes into account the visibility range, angle of view and wind direction.

The method for visual impact assessment of wind turbines proposed in this paper fulfills the requirements of The Guidelines for Landscape and Visual Impact Assessment [39], which

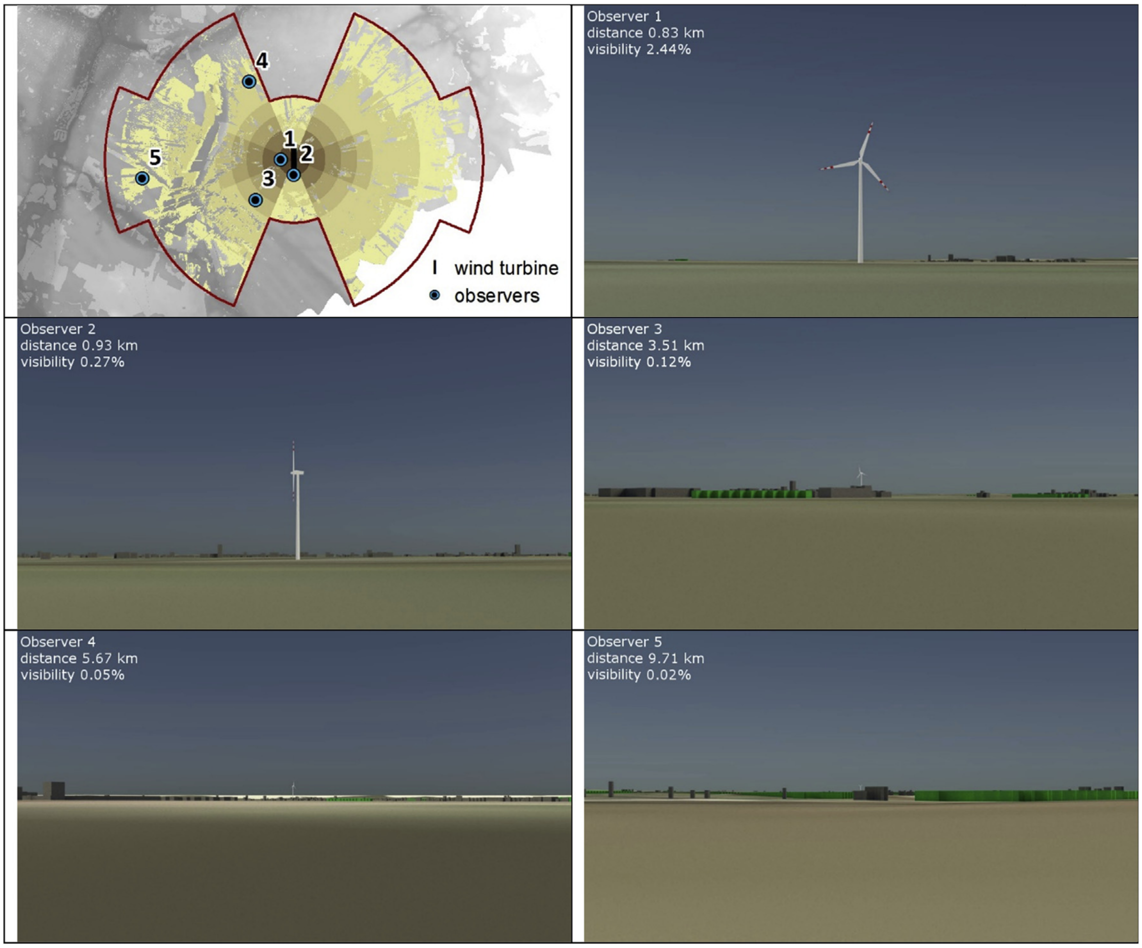

Fig. 13. Results of 3D visualizations made in Blender software for different observer positions of the turbine impact (animations).

recommend that the analysis take into regard the visibility range, visibility extent and duration.

The method proposed in this paper can be successfully used for evaluation of the wind turbine impact on the environment. It provides the visibility of a wind turbine within the range of actual impact rather than visualization of the maximum distance from which the wind turbine is seen. Analyses simply giving the maximum area of sight of a wind turbine without additional detail are often received with unjustified anxiety by inhabitants of a given area. The method proposed in this paper includes the possibility to

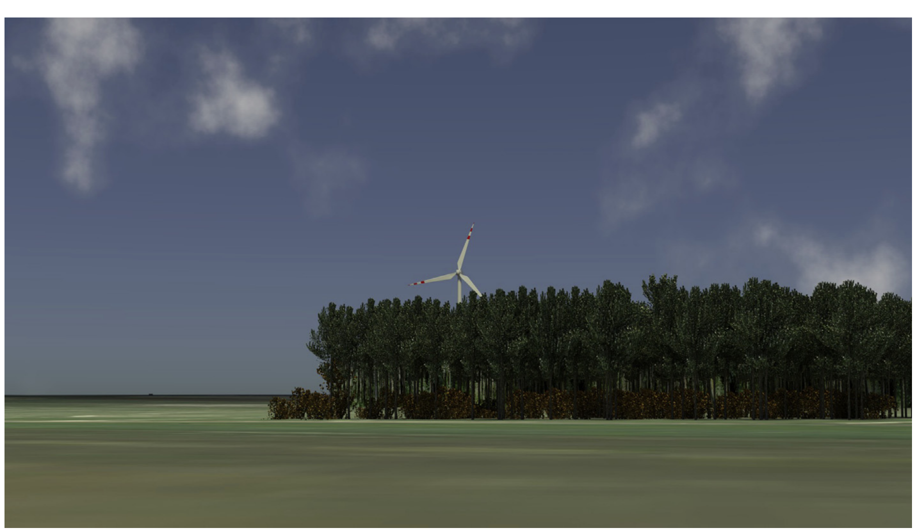

Fig. 14. Realistic render (animation).

quickly develop realistic renders and animations (Fig. 14) from any localization in the study area, which gives the opportunity for interpretation of the results also by laymen. It can be also very helpful in planning locations for new wind turbines.

5. Conclusion

1) The proposed method permits a gradual evaluation of visual impact assessment performed taking into account the spatial extent, visible range, angle of view and wind direction.
2) The visual impact assessment of 150 m tall wind turbines should by conducted at 12 km at maximum.
3) The Blender software can be a useful tool for quantified evaluation of wind turbine visibility from any site on the basis of the area taken by the turbine relative to the field of view.
4) The method proposed is universal and can be effective in the terrain of different landscape and type of coverage.
5) The combination of GIS and 3D techniques permits a simple interpretation of results.
6) The Blender software for 3D animation in cooperation with GIS tools can be useful for the choice of optimum localizations of a wind turbine.
7) The realistic render visualizations provided by the Blender software can be used for making presentations at the stage of consultations with inhabitants of a given area.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2016.05.016.

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