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Minimizing light pollution from wind turbines lighting

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1. Introduction

Global energy and environmental concerns have resulted in the development of renewable energy technologies, aiming at mitigation of climate change issues, as well as rapid environmental degradation. Among various innovative solutions, wind turbines became one of the most accessible, widespread, and increasingly stable renewable energy recourses. Despite significant sustainable benefits of wind energy, inter alia, carbon neutrality, investment attraction, and job creation, wind turbines have, however, notable impacts on the environment and local communities, in particular, they contribute to an increase in artificial light at night (ALAN) levels and, thereafter, increases light pollution. This paper discusses (1) the impacts of lighting emitted from wind turbines, (2) requirements for wind turbine lighting, (3) dark sky protection principles, and (4) the evolution of lighting requirements towards minimizing the negative effects of wind turbines ALAN. The main goal is to address the adverse impacts introduced by wind turbine lighting and suggest the implementation of dark sky protection principles to minimize these effects.

2. Light pollution: adverse impacts

Light pollution is one of the most fast-growing forms of environmental degradation that is caused by the increased amount of artificial light at night (ALAN). This new environmental problem started to be gradually recognized within the political and legal agenda due to broad research findings, indicating various adverse impacts of ALAN. Light pollution can be defined as every form of artificial light in the wrong place at the wrong time which creates a sky glow, glare, nuisance, and other relevant causes of environmental degradation including some properties of artificial light which emit non-environmentally friendly or inappropriate light [1].

The increased nighttime brightness is a concern in many areas. The most obvious negative effect of light pollution is the disappearance of the dark skies, leading to the inability to see the stars and starlight. Apart from that, light pollution causes serious health deterioration effects and contributes to further degradation of the environment. With regard to human health, scientific research has found that prolonged ALAN exposure can lead to the incidence of certain health issues, including insomnia, cardiovascular disease, obesity, hormone-dependent cancer, and various mental disorders [2],[3]. The adverse environmental impacts of ALAN are also well evident. To give some examples, light pollution contributes to climate change, has direct and indirect effects on different species, inter alia, migration birds, bats, and turtles, alters natural habitats, and harms ecosystem functioning [4]. In addition, increased nighttime lighting reduces public safety, creates a nuisance, and leads to inefficient energy consumption [5].

Turning to light pollution issues, researchers consider different types and sources of lighting. Light emitted from wind energy turbines has also received attention in terms of its negative effects. Wind turbines are not considered the main sources of light pollution, but nonetheless, they introduce additional light that can affect

local environments, causing further alteration of species behaviour and ecosystems, as well as worsening the well-being of the local population. Various bird species, for instance, are attracted to light emitted from wind turbines and as a consequence, such nighttime lighting influences the risk of mortality due to collisions with these energy structures [6]. Wind turbine lighting also contributes to the disorientation of different migratory species and the disturbance of habitats [7].

The most notable negative impact of wind turbine lighting is manifested in the disturbance of local communities. Wind turbine flashing lights became a serious obstacle to social acceptance of wind energy and, in some cases, have led to the cancellation of wind energy projects as a result of successful judicial proceedings initiated by locals. Research has shown that the annoyance caused by obstruction lights can have a significant effect on a number of residents, therefore, the reduction of the light nuisance may also reinforce a positive perception of wind energy [8]. In 2019, more than one hundred residents filed a complaint in the Supreme Court of New York against EDP Renewables, the developers of the Arkwright Wind Power, indicating the emergence of health issues and inability to properly enjoy their properties due to, in particular, increased nighttime lighting and constant flashing red lights [9]. One of the recent examples is the decision of the Toulouse Court of Appeal in 2021 [10]. The court granted a compensation of €110,000 for health deterioration linked to "wind turbine syndrome". The flashing light from wind turbines was mentioned among the factors that caused significant health deterioration, including insomnia and fatigue.

The adverse impacts of light pollution discussed above highlight the need to take into account the potential effects that may be introduced by turbine lighting during different stages of wind energy project development.

3. Lighting for wind turbines

The requirements for the installation of lighting for wind turbines stem from the need to ensure aviation safety. This type of lighting is called obstruction or warning lighting and is used to improve the visibility of structures or fixed obstacles that may impede safe aircraft flights. An obligation to install obstacle lights depends mainly on the height of the wind turbine and starts from 150 meters, which corresponds to a minimum flight altitude.

At the international level, the obligation for obstruction lighting is established by the regulations adopted by the United Nations International Civil Aviation Organisation (ICAO). ICAO was founded upon the adoption of the Chicago Convention on International Civil Aviation on 7 December 1944 (hereafter – *Convention*) and aims at ensuring international aviation safety [11]. Section 6.2.4. of Volume 1 of Annex 14 to the Convention is specifically dedicated to the recommendations on the lighting for wind turbines [12]. ICAO recommends using lights of medium or low intensity in accordance with the height. During the day and twilight conditions white, flashing lights with an intensity of 20,000cd should be used, while during the night, white or red flashing or red steady light of 2,000cd intensity are recommended. The ICAO recommendations specifically address the issues related to installations of lighting throughout wind farms. The latter includes several aspects to be considered, inter alia, the perimeter of the wind farm, requiring the illumination of wind turbines along the perimeter, simultaneous flashing requirements, and, depending on the height, additional lighting shall be installed. The same approach should be applied if the light is deemed necessary for a single wind turbine or short line of wind turbines. Despite providing all the necessary requirements needed for aircraft safety, the international recommendations, however, fail to address negative effects that may be introduced with obstruction light, thereby do not provide for any light mitigation measures.

National requirements for obstruction lighting for wind turbines are diverse, although several countries tend to adopt the recommendations developed by the ICAO. According to the USA requirements, for instance, wind turbines should have nighttime red flashing, strobe, or pulsed lighting of 2000cd [13]. The number of lights differentiates depending on the height of the structure. The US standards do not require any lights during the daytime and establish separate requirements for obstruction lights for offshore wind turbines. Canadian Aviation Regulations [14] require the installation of either red constant or flashing with the intensity of 2000cd or white flashing lights with the intensity of 20,000cd, depending on the part of the day and the height of the turbines. The wind farms should be illuminated around the perimeter with red flashing lights. Interestingly, the Canadian regulations do not define specific lighting configurations for onshore and offshore wind turbines. In addition, obstruction lighting is required throughout the whole day. Regarding European Union member states, the approaches to obstruction lighting are also different due to the absence of unified regulations at the EU level. A number of states, including Poland and the Netherlands, impose an obligation to install lighting on wind turbines throughout the whole day, while other states, such as Belgium, Germany, and Denmark, consider only nighttime lighting sufficient for safety purposes [15]. The intensity requirements vary between 2,000cd to 200,000cd in the

daytime and 100cd to 100,000cd in the nighttime. National regulations on obstruction lighting, in general, demand high illumination levels of wind turbines.

4. Light pollution mitigation principles

International recognition of light pollution as a global problem has led to the development of five dark sky protection principles, which aim to ensure the implementation of sustainable and responsible outdoor lighting practices [16]. These principles are directed to any type of outdoor ALAN, thereby their implementation can significantly improve wind turbine lighting requirements. The first principle is the purposeful use of any outdoor lights. Since obstruction lights have already clearly defined purpose, namely aviation safety, the requirements for wind turbine lighting comply with the first principle. The second principle is contained in the need to direct the lighting only where it is necessary. In a view of wind turbines, the implementation of this principle is rather difficult in terms of preventing collisions with aircrafts, however, attempts should be taken to prevent floodlighting. The principle of low light levels is the third dark sky protection principle. The amendments to the requirements should be related to minimizing the intensity of nighttime lighting to levels that will ensure aviation safety and simultaneously will not disturb local residents and the environment. Another responsible outdoor lighting principle requires control over the use of lights, in other words, lighting should be used only when it is necessary. To decrease light pollution levels from wind turbines, light mitigation technologies can be used, allowing the possibility of dimming or complete shutdown of ALAN when not needed. The last principle to be implemented wind turbines should be equipped with lights of warmer colours to limit the amount of shorter wavelength (blue-violet) light that is the most harmful to human health and biodiversity.

5. Evolution of lighting requirements

The increased awareness of the negative effects produced by wind turbine lighting has resulted in positive changes of obstruction light requirements. Several countries, such as the USA, Canada, Germany, Norway, The Netherlands, and Sweden, have attempted to minimize light pollution levels by adopting measures to introduce light mitigation technologies. The following technologies are commonly accepted: (1) aircraft detection lighting systems (ADLS) and (2) light intensity reduction systems (LIRS).

ADLS is a system designed to automatically activate obstruction lights upon detection of the approaching aircraft. Some countries provide for the establishment of warning zones for ADLS. The warning zone extends outward from the impact boundary to the detected aircraft, thus, determining the moment of the lighting activation. The USA, for instance, requires the lighting to be activated if an aircraft is at or below 1,000 feet above the tallest wind turbine and is approaching a three statute mile (4.8 kilometres) perimeter around the wind energy structures [13]. In other countries, the activation of ADLS is related to the speed of aircraft, e.g., in Canada. The installation of ADLS is subject to approval by authorized bodies. In addition, although in most cases ADLS for wind turbines is not obligatory, some countries establish a mandatory requirement for the installation of such systems. To give an example, Germany became the first European state that introduced the “on-demand” approach to warning lights and made ADLS compulsory for all wind turbines requiring obstruction markings: onshore until 12/31/2022 and wind farms offshore until 12/31/2023 [17].

LIRS is used to reduce the intensity of obstacle lighting with regard to visibility. The wind turbine is equipped with sensors to control visibility conditions. Light dimming can be allowed up to 30% with the visibility is 5 km and more and up to 10% less when the visibility is 10 km and more. LIRS is adopted across various jurisdictions, inter alia, the USA, Canada, Germany, France, Poland, and Belgium. Similar to ADLS, the possibility to install light dimming systems is subject to approval by authorized authorities.

With recent amendments to the existing wind turbine lighting requirements, some innovative measures for light pollution mitigation were introduced. Several countries, by opting for constant and stable ALAN, have prohibited flashing lights. Other improvements affected offshore wind turbines. Thus, direct lighting of surface water was prohibited while indirect lighting of surface water has to be minimized to prevent negative impacts on marine biodiversity. Moreover, some countries require to optimize the obstruction lighting so that they are directed only where it is needed. The latter should be determined for each project separately. In addition, several countries, including the Netherlands, are testing different light mitigation technologies in order to adopt regulatory changes in the near future.

6. Conclusions and recommendations

The current requirements for wind turbine lighting are focused on the need to ensure aviation safety, thereafter, they are highly demanding and result in significant illumination that causes light pollution. At the same time, however, there is a growing tendency to introduce light mitigation technologies for minimizing ALAN-induced impacts on communities and the environment, providing that such technologies do not diminish the necessary safety levels.

Newly introduces amendments are consistent with the main dark sky protection principles. The further incorporation of these principles, including through the implementation of light mitigation technologies, will contribute to the spread of wind energy due to greater public acceptance and reduction of the potential negative impacts of wind turbines caused by obstruction lighting. Nevertheless, it should be noted that the introduction of light mitigation solutions should be followed by the adoption of unified requirements for these technologies to prevent extensions of periods for project approval. In addition, light pollution mitigation measures should be also included in international and regional obstruction lighting regulations and recommendations.

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