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Review

# Environmental issues associated with wind energy – A review

Kaoshan Dai [a, b, *], Anthony Bergot [c], Chao Liang [d], Wei-Ning Xiang [e, f], Zhenhua Huang [g]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering and College of Civil Engineering, Tongji University, 1239 Siping Rd., 200092 Shanghai, China
[b] State Key Lab of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400044, China
[c] ENSI de Bourges, 88, Boulevard Lahitolle, 18020 Bourges cedex, France
[d] College of Civil Engineering, Tongji University, 1239 Siping Rd., 200092 Shanghai, China
[e] Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, East China Normal University, 500 Dongchuan Rd., 200214 Shanghai, China
[f] Department of Geography and Earth Science, University of North Carolina, Charlotte, 9201 University City Blvd., Charlotte, NC 28223, USA
[g] Department of Engineering Technology, University of North Texas, 3940 N. Elm Street F115M, Denton, TX 76207, USA

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ABSTRACT

Recognized as one of the most mature renewable energy technologies, wind energy has been developing rapidly in recent years. Many countries have shown interest in utilizing wind power, but they are concerned about the environmental impacts of the wind farms. The continuous growth of the wind energy industry in many parts of the world, especially in some developing countries and ecologically vulnerable regions, necessitates a comprehensive understanding of wind farm induced environmental impacts. The environmental issues caused by wind farms were reviewed in this paper by summarizing existing studies. Available mitigation measures to minimize these adverse environmental impacts were discussed in this document. The intention of this paper is to provide state-of-the-art knowledge about environmental issues associated with wind energy development as well as strategies to mitigate environmental impacts to wind energy planners and developers.



## 1. Introduction

Combustion of fossil fuels is believed to be one of the primary factors contributing to global warming. Energy researchers, industrial professionals, and government decision makers have increasingly turned their attention to renewable energy sources in an effort to reduce reliance on fossil fuels. Energy technologies such as biomass, wind, and geothermal are developing very fast and are becoming more commercially competitive [1]. According to the predictions of the European Renewable Energy Council, about half of the total global energy supplies will come from renewable energy in 2040 [2]. Johansson et al. [3] predicted that there would be a large increase in renewable energy production and efficiency before 2050. This increase of renewable energy use should lead to a substantial decrease of carbon dioxide emissions.

As one of the most mature renewable energy technologies, wind power has seen accelerated growth during the past decade. Wind power has become the preferred option of energy for planners and national governments, who are seeking to diversify energy resources, to reduce $CO_2$ emissions, to create new industries, and to provide new employment opportunities. According to the latest Global Wind Report, the total global wind power installation was 318.105 GW at the end of 2013 [4]. However, wind energy developments are not free of adverse environmental impacts. A poor understanding of these environmental impacts is a serious concern for the wind energy industry especially in developing countries and ecologically vulnerable regions [5,6].

In this paper, the authors reviewed potential environmental issues caused by wind farm developments, summarized evidence collected through existing case studies, and identified methodologies to mitigate these adverse environmental impacts. This review study provides energy industry planners and developers with an understanding about how an inappropriate wind farm project design could adversely affect a local environment. Mitigation efforts should be completed during the design, construction, and operation phases of a wind farm in order to avoid damages to vulnerable ecological systems.

* Corresponding author. State Key Laboratory of Disaster Reduction in Civil Engineering and College of Civil Engineering, Tongji University, 1239 Siping Rd., 200092 Shanghai, China. Tel.: +86 2165981033.
*E-mail addresses:* kdai@tongji.edu.cn (K. Dai), anthony.bergot@ensi-bourges.fr (A. Bergot), liangchao_tongji@126.com (C. Liang), wnxiang@mail.ecnu.edu.cn (W.-N. Xiang), zhenhua.huang@unt.edu (Z. Huang).

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## 2. Wind energy induced environmental issues

A wind power plant uses wind turbines to convert wind energy into electricity or mechanical energy. The output power of a turbine is the function of the density of the air, the area swept by the turbine blades, and the cube of the wind speed [7]. The primary environmental issues related to wind turbine usage include wildlife safety, bio-system disturbance, noise, visual pollution, electromagnetic interference, and local climate change [8,9]. These issues can be grouped into ecological effects, impacts on humans, and climate-related issues [10,11].

### 2.1. Effects on animals

#### 2.1.1. Birds

Wind turbines induce mortality and disturbance risks to birds. Birds can be killed by colliding with the rotating propellers of a wind turbine or can suffer lethal injuries because of collision with the turbine towers, nacelles or other structures in a wind farm such as guy cables, power lines, and meteorological masts [12]. Loss et al. [13] estimated that 234,000 birds on average were killed annually by collisions with monopole wind turbines in the U.S. Saidur et al. [5] reported that bird fatality rates at different regions of the U.S. average 2.3 birds per turbine per year for wind turbines with rotor diameters ranging from 33 m to 72 m. Although birds have been killed by pesticides or collisions with other human-made structures, including fossil fuel infrastructures [14], the adverse effects of wind farms on birds cannot be ignored. In addition, wind turbine towers were found to have killed birds from some rare species such as golden eagles, swans [15], and Cantabrian Capercaillies [16]. Because researchers used different methods to calculate the number of bird fatalities [17], it is unrealistic to compare the mortality numbers in these studies. The accurate bird fatality rate is difficult to estimate due to variations in search area, searcher efficiency and predator removal rates [18,19]. The number of fatal bird collisions varies by different locations. Even in the same location, differences still exist among different groups of wind turbines [20]. The wind turbine induced bird mortality data in publications are summarized in Table 1.

Various factors contribute to wind turbine induced bird mortality, such as the wind turbine design and arrangement, bird species, and climatic variables. Orloff and Flannery [21] reported that bird mortality was higher for lattice turbines than for other turbine tower types. The location and layout of the wind farm also have influence on the bird mortality rate. The approaching angle between the bird flight path and the turbine orientation showed a significant correlation with collision probability [22]. The end of turbine strings, the edge of the gap in the strings, and the wind turbine cluster's edges were the most dangerous places for birds [23]. The bird mortality rate increased in areas where turbines are located on ridges, on upwind slopes, or close to the bird migration routes [24–26]. For example, if a wind farm is on a bird migratory route, birds have to avoid the wind farm and deviate from their usual route. The extra deviation work will increase the energy expenditure of the birds and reduce their survival rates [27,28]. This wind farm barrier effect on birds is species-specific. In fact, bird mortality was found to be associated with the bird species [29]. Orloff and Flannery [21] observed that golden eagles, red-tailed hawks, and American kestrels were killed more often than turkey vultures and ravens. This may be attributed to the foraging behaviors or flight characteristics of these birds. Desholm [30] used two indicators, the relative abundance and the demographic sensitivity, to characterize the sensitivity of the collisions of birds and wind turbines. Langston and Pullan [25] suggested considering diurnal and nocturnal phenomena as well to characterize the same problem because birds behave differently during these scenarios. Bad weather and light conditions, such as fog, rain, strong wind, or dark nights, can decrease the visibility and the flying height of birds. This may result in more collisions [12,25,26]. However, the correlation between the collisions and poor weather and light conditions has not yet been clearly identified because of the difficulty of observing birds in these conditions. Seasons are also a factor; Smallwood and Thelander [23] found that more bird fatalities occurred at wind turbines during the winter and summer months. Although there are many studies, the correlation between wind turbine induced bird mortality and many other variables such as turbine types and topographic features have not yet been established. Because there are so many complicated factors that contribute to the relationship between bird mortality and wind turbines, special efforts should be made when comparing data of different studies.

Another negative impact of wind turbines on birds is disturbance, which includes habitat destruction, the barrier effect, and impact on the bird breeding and feeding behavior. Construction of wind turbines and associated infrastructures may cause destruction of local birds' habitat [25,31]. Some wind turbines can also create physical barriers that obstruct birds from access to their natural feeding grounds and roosting locations. Noises and turbulent air currents produced by the wind turbines' operation may scare birds away and narrow their territories, which can also affect birds' foraging behavior. Construction of power lines and roads for wind farms may create other obstacles for birds. It was found that prairie birds tried to avoid power lines and road construction sites by at least 100 m [32]. Power lines and roads themselves may also cause extensive habitat fragmentation and provide an invasion path for exotic species [33]. Christensen et al. [34] studied birds' behaviors with radar tracking. He concluded that 14%–22% of the birds increased their flying altitude to pass through the studied wind farm. Additionally, the majority of the birds either changed their flying direction to bypass the wind farm by a distance of 400 m or 1000 m or completely disappeared from the radar screen [34]. Similar bird re-orientation behaviors were observed by Kahlert

**Table 1**
Bird collision mortality caused by wind turbines [18,29,150,151,152].

| Bird mortality: /turbine/year | Location and time | Turbine information | Reference |
|---|---|---|---|
| 24 birds | East dam, Zeebrugge (2001–2002) | 200, 400, and 400 kW | [18] |
| 35 birds | Boudewijn canal, Brugge (2001–2002) | 600 kW | [18] |
| 18 birds | Schelle (2002) | 1.5 MW | [18] |
| 0.27 birds | Straits of Gibraltar (1993/12–1994/12) | 1.0–1.8 MW with the rotor diameter between 18 m and 23 m | [29] |
| 0.03 birds | Tarifa, Spain (1994/7 to 1995/9) | 66 turbines (total 10 MW) with 20 m diameter rotors | [150] |
| 0.186 vultures | Tarifa, Cadiz, Spain (2006–2007) | 296 turbines (0.3–2.2 MW) with rotor diameter 56–90 m | [20] |
| 0.145 vultures | Tarifa, Cadiz, Spain (2008–2009) | 296 turbines (0.3–2.2 MW) with rotor diameter 56–90 m | [20] |
| 3.59 birds | Nine Canyon Wind Power Project (2002/9-2003/8) | 37 1.3-MW turbines with approximately 62 m rotor diameter | [151] |
| 1.33 birds | Tarifa, Andalusia, Spain (2005–2008) | 252 turbines ((0.3–2.2 MW) with rotor diameter 56–90 m | [152] |

et al. [35] in his study at the Nysted wind farm. Langston and Pullan [25] studied the impacts of wind farms on breeding, feeding and roosting behaviors of different bird species. The study reported that even though the wind turbine showed no impact on the bird population and distribution of Eurasian oystercatchers, northern lapwings, and common skylarks found within a one km range around the wind farm, negative effects on the birds' breeding, feeding, and roosting behaviors were observed for common redshank and black-tailed godwits within a 200-m range around the wind farm. Additionally, the feeding and roosting behaviors seem to be more sensitive than the breeding behavior [25]. Another research study found that, through 10 years of observation data on 47 eagle territories in western Norway, coastal wind farms affected the breeding success rate of the white-tail eagles [36].

#### 2.1.2. Bats

Bats are more likely to respond to moving objects than stationary ones [37]. However, a high bat mortality rate close to wind farms has been observed. Wind turbine related bat mortalities are now affecting nearly a quarter of all bat species in the United States and Canada [38]. Research revealed that wind turbines killed not only bats from local populations but also migratory bats [39]. However, researchers are not in agreement about the reasons for the bat mortalities [40,41]. Early studies concluded that bats were killed by the sudden pressure drop near the turbine edges, which caused the bats to suffer barotrauma and internal hemorrhaging [42]. Barotrauma-related internal hemorrhaging was found in over 50% of the dead bats [43]. More recent research found that impact trauma was responsible for the majority of the turbine-associated bat deaths [44,45]. Other researchers proposed alternative explanations. According to Arnett et al. [46], bats could be attracted by the ultrasound emissions and the lights of the wind turbines. However, this hypothesis needs to be proven through further research. Another possibility is that the bats treated the wind turbines as trees and tried to explore them as potential roosting sites. In addition, a large amount of insects attracted by the high heat radiation of the wind turbine nacelles could also cause the hunting bats to aggregate around the turbines [47,48].

Kunz et al. [49] observed that a large number of dead bats were found at utility-scale wind energy facilities located along forested ridge tops, although bat carcass search is easier in grassland areas compared to agricultural landscapes or forested ridge tops. Marsh [15] indicated that the wind farms on the forested ridges were more dangerous for bats. Additionally, more bats were killed in autumn migration and during the two-hour period after sunset [15]. According to Kerns and Kerlinger [50], weather conditions and bat mortality do not seem to be directly associated. The bat fatality rate did not change when the wind speed was faster, when the environmental temperature was lower, or during foggy conditions. The flashing red aviation lights on the top of the wind turbine towers were not a reason for the bat mortality [51]. A study by Barclay et al. [52] showed that the size of the rotor was not associated with the death toll of bats, but the height of the turbine tower was. The bat mortality rate increased exponentially as tower height increased [52]. This brought up a new concern: future wind farms will have less wind turbines but each turbine will be higher; this may increase bat mortality. A comprehensive bibliography associated with the wind farm induced bat morality rate up to 2008 can be found in Ref. [53].

#### 2.1.3. Marine species

Offshore wind turbines may have impacts on marine species. Construction of wind turbine foundations and on-site erection of wind turbine towers make seawater turbid and introduce additional objects on the seabed, which may cause damages to the benthic fauna and flora and may block sunshine in the water. Wind turbines and their scour protection may change the nearby fish distribution. Wind farm construction creates an artificial reef, which also impacts biodiversity. Research on two Danish wind farms [54] indicated that, around the foundation of the turbines, the abundance and diversity of the benthic communities increased more than the native infauna communities. Studies also showed that wind turbines built in seawater increased the fish populations considerably, possibly because of the enhanced resident food supplies on the turbines [55,56]. However, Berkenhagen et al. [57] believed that if the cumulative effect was considered, the offshore wind farms would induce a substantial effect on fisheries. In particular, the opportunities to catch valuable species would be considerably reduced. However, other studies indicated that, within a time window of seven years after construction, the studied offshore wind farm showed neither a direct benefit nor a definite threat to fish diversity [58] as well as sandeels and their sand habitat [59].

The noise and the electromagnetic fields around wind turbines may lead to negative effects on fish [60]. Marine mammals such as porpoises and seals may react to wind farms, especially during construction phase activities such as pile driving [54,61]. At the Nysted Offshore Wind Farm, researchers observed a clear porpoise population drop during construction and operation of the wind farm, which persisted for two years [54]. Wind turbine maintenance activities, such as parts replacement or lubrication, can cause oil or waste to enter and pollute the surrounding seawater. Although research results in literature [62] claimed that the potential impacts of wind farms on marine life were mainly within the construction phase and the impacts during the operational phase were more local, marine wind farms should be carefully planned to avoid major habitats of local sea animals.

### 2.2. Deforestation and soil erosion

During construction of a wind farm, some activities such as foundation excavation and road construction, may affect the local bio-system. If surface plants are removed, the surface soil would be exposed to strong wind and rainfall, resulting in soil erosion. Wastewater and oil from the construction site may seep into the ground soil and lead to serious environmental problems. Areas with rich wind resources, including grasslands, moorlands and semi-deserts, typically have weak eco-systems with low bio-diversity. Construction with heavy machinery may disturb the local eco-balance, and the local environment's recovery may take a long time A Chinese wind turbine construction guideline [63] suggested that excavation should involve human labor as much as possible in order to minimize the disturbance induced by the heavy machines. In addition, the guideline recommends that trees and grasses should be replanted as soon as possible after construction.

### 2.3. Noise

Noise is one of the major environmental hindrances for the development of the wind power industry. According to Van den Berg [64], during quiet nights, people reacted strongly to the wind turbine noise in the range of 500 m surrounding the wind farm and experienced annoyance in the range of 1900 m surrounding the wind farm. It was also found that people were more annoyed by wind turbine noise than by transportation noise [65]. In addition, wind turbine induced visual and aesthetic impacts on the landscape could cause people to be more annoyed [65]. However, compared to the large quantity of data on transportation noise induced annoyance, studies on the correlation between annoyance and wind turbine noise are limited.

Two types of noise are produced by wind turbines: tonal and broadband noises. Tonal noise is defined by discrete frequencies (in the range of 20 Hz–100 Hz) and is generated by the non-aerodynamic instabilities and unstable airflows over holes, slits, or a blunt trailing edge of a wind turbine [66]. Broadband noise, a random, non-periodic signal with a frequency more than 100 Hz, contains continuous frequency distribution generated by the interaction of wind turbine blades with the atmospheric turbulence and by the airflow along the airfoil surface [66]. The noise of the wind turbines includes aerodynamic noise and mechanical noise. Aerodynamic noise comes from the turbine blades passing through the air. This noise, perpendicular to the blade rotation surface, varies with the turbine size, the wind speed, and the blade rotation speed. A strong wind with a big turbine is obviously noisier. Since modern turbines can rotate to face the wind upward direction, noises can come from different directions at different times. Some turbine blade pitches also can automatically adjust with the change of wind direction which produces different levels of noise. Aerodynamic noise contains different frequencies and is considered to be a broadband noise [67]. Mechanical noise comes from the turbine's internal gears, the generator, and other auxiliary parts [68]. These noises are noticeable and irritating, especially for wind turbines without sufficient insulation [67]. Contrary to the aerodynamic noise, mechanical noise does not increase with the turbine dimensions, and it can be controlled through proper insulation during manufacturing [69]. The total noise, measured by the sound pressure level dBA, is a combination of the mechanical and the aerodynamic noises. The low frequency noises (10–200 Hz) are considered as the substantial part of the noises when the modern turbines become larger [70].

Early acoustic noise testing was performed on several small-size wind turbines [71–77]. Recent studies on utility-scale wind turbines showed that the sound pressure level at 40 m away from a single turbine can vary from 50 to 60 dBA [78]. In a wind farm, the noise level at a certain distance from a group of wind turbines is also related to the number of turbines in operation. For example, the sound pressure level in a house located at 500 m away from a single wind turbine normally varies from 25 to 35 dBA. At the same distance, the noise level generated by 10 operating wind turbines can range from 35 dBA to 40 dBA [78].

Many other factors contribute to noise propagation and attenuation, including air temperature, humidity, barriers, reflections, and ground surface materials. For example, inside a building, the wind direction and the building material sound absorption ability have influence on the attenuation of the noise [67]. Another important factor is the background noise. At night, noises can be perceived differently. The whooshing (amplitude-modulated noise from wind turbines) can be perceived with increased intensity and can even become thumping. This is due to the ambient noise or background noise being low at night as a result of low human-made noise and the stable atmosphere [7]. According to Van den Berg [64], during an otherwise quiet night, a person living 1.5 km away from a wind farm perceives the wind turbine noise as an “endless train”. However, if the wind farm was located on the seashore, where background noises from the waves and the wind are loud, wind turbine induced noise cannot be differentiated from the ambient noise. Therefore, when analyzing wind turbine noise, the measured noise pressure level of wind turbines should be modified by the background noise.

To control the noise level, a minimum separation distance between wind farms and habitations is usually recommended by governments or medical institutions and varies among countries or regions, which are summarized in Table 2. Another approach to control the noise level is to set an upper limit dBA value that can be heard at the closest inhabited dwelling. Such restrictions for different countries or regions are collected in Table 3. The $L_{90}$ in Table 3 measures the noise level that is exceeded during 90% of the time, and it represents the noise level someone can hear in the late evening or at night when there is very little background noise [79]. $L_{90}$ is useful because it minimizes the background noise effects that mask the noise of wind farms [80,81]. Kamperman and James [79] argued that using a single A-Weighted (dBA) noise descriptor, which approximates the response of human hearing to medium intensity sounds, is not adequate to limit the wind turbine noise that has significant low frequencies. To supplement the current standards, Kamperman and James [79] proposed to limit the C-Weighting (dBC) noise within $L_{90}$ + 20 dB and 50 dBC maximum [79]. The C-Weighting approximates human hearing to loud sounds and can be used for low-frequency sound measurement.

Noise can induce sleep disturbance and hearing loss in humans. Exposure to high frequency noises can trigger headaches, irritability, and fatigue, as well as constrict arteries and weaken immune systems [82]. Disturbing noises can also induce negative subjective effects such as annoyance or dissatisfaction [81]. Shepherd et al. [83] conducted a questionnaire study on people who lived within 2 km of wind turbines. Results showed that the wind turbines affected life quality and amenity for some residents. Those residents were not willing to accept wind turbines and kept a virulent attitude against wind turbine projects. Other studies also showed

**Table 2**
Recommended distances between wind farms and habitations [143,144,145,146,147,148].

| Region | Distance (m) | Reference |
|---|---|---|
| England (U.K.) | 350 | [143] |
| Scotland (U.K.) | 2000 | [143] |
| Wales (U.K.) | 500 | |
| Belgium | 350 in theory (developers making it no closer than 500) | [144] |
| Denmark | 4 × the total height | [144] |
| France | 1500 (in practice 500 seems minimum observed) | [144] |
| Germany | Between 300 and 1500 | [144] |
| Italy | Between 5 × the height or 20 × the height (not specified if mast or total height) | [144] |
| Netherlands | 4 × the height of the mast | [144] |
| Northern Ireland | 10 × rotor diameter (with a minimum distance of 500) | [144] |
| Romania | 3 × height of the mast | [144] |
| Spain | Between 500 and 1000 | [144] |
| Switzerland | 300 | [144] |
| Sweden | 500 (in practice) | [144] |
| Western Australia | 1000 | [145] |
| Manitoba (Canada) | 500–550 | [146] |
| Ontario (Canada) | 550 | [145] |
| Prince Edward Island (Canada) | 3 × the total height | [145] |
| Illinois (U.S.) | 3 × the total height of the tower + the length of one blade | [147] |
| Kansas, Butler County (U.S.) | 304.8 | [147] |
| Kansas, Geary County (U.S.) | 457.2 | [147] |
| Massachusetts (U.S.) | 1.5 × total height | [147] |
| Minnesota (U.S.) | At least 152.4 and sufficient distance to meet state noise standard | [147] |
| New York (U.S.) | 1.5 × total height or 457.2 m | [147] |
| Oregon (U.S.) | 1000 | [145] |
| Door County, Wisconsin (U.S.) | 2 × total height and no less than 304.8 | [147] |
| Portland, Michigan (U.S.) | 2 × total height and no less than 304.8 | [145] |
| North Carolina (U.S.) | 2.5 × total height | [145] |
| Dixmont, Maine (U.S.) | 1609 | [145] |
| China | 200 for a single wind turbine, 500 for a large wind farm | [148] |

**Table 3**
Noise limits in different regions [79,144,145,149].

| Country/region | Noise limits | Reference |
|---|---|---|
| UK | 40 dBA (day) and 43 dBA (night) or $L_{90}$ + 5 dBA | [79] |
| Denmark | 40 dBA | [79] |
| France | $L_{90}$ + 5 dBA (day) and $L_{90}$ + 3 dBA (night) | [79] |
| Germany | 50 dBA (day) and 40 or 35 dBA (night) | [79] |
| Belgium | 49 dBA (day) and 39 dBA (night) | [145] |
| Netherlands | 40 dBA | [145] |
| Portugal | 55 dBA (day) and 43 dBA (night) | [145] |
| Sweden | 40 dBA | [145] |
| Holland | 40 dBA | [79] |
| Australia | $L_{90}$ + 5 dBA or 35 dBA | [79] |
| Oregon (U.S.) | 36 dBA | [145] |
| New York (U.S.) | 50 dBA | [145] |
| North Carolina (U.S.) | 55 dBA | [145] |
| Maine (U.S.) | 55 dBA (day) and 45 dBA (night) | [145] |
| Illinois (U.S.) | Octave frequency band limits about 50 dBA (day) and 46 dBA (night) | [79] |
| Wisconsin (U.S.) | 50 dBA | [79] |
| Michigan (U.S.) | 55 dBA | [79] |
| Ontario (Canada) | 45 dBA (in urban and suburban areas) and 40 dBA (in rural areas) | [144] |
| British Columbia (Canada) | 40 dBA | [145] |
| Alberta (Canada) | 50 dBA (day) and 40 dBA (night) | [145] |
| Québec (Canada) | 40 dBA | [145] |
| China | 55 dBA (day) and 45 dBA (night) | [149] |

that sleep deprivation due to the wind turbine noise can cause serious health problems. However, studies have not yet proved that these noise *per se* directly cause health problems or that the infrasound from the wind turbines directly impacts the vestibular system [7]. Due to the paucity of literature and the fact that annoyance can be caused by many other factors, more rigorous studies are needed to find a clear association between annoyance and wind turbine noise.

### 2.4. Visual impact

Shadow flicker, an effect caused by the movement of the turbine blades through the sunshine, becomes a human impact when a number of parameters converge, including distance from turbine, operational hours, and interactions with the sunlight [84]. Besides the flickering shadows, the negative visual impact of wind farms on landscapes is another factor that makes people have a negative opinion of the wind energy industry [85]. A study by Bishop [86] revealed that during days with clear skies, wind turbine towers can be seen from as far as 30 km. With the trend of constructing new wind turbine towers that are taller than their predecessors [87], the visual impact problems of the wind turbines cannot be ignored anymore. However, this problem is subjective. People's positive or negative attitude may depend on their perception on the unity of the environment, their personal feeling towards the effects of wind turbines on the landscape, and their general attitude about the wind energy industry [88]. Some may consider wind energy as a useful alternative to reduce the conventional energy induced negative consequences on the environment while others may look at the wind turbines as machines that are changing a beautiful landscape into an industrial environment [89].

Evaluating the visual impact of a wind farm is a difficult task [90]. Thayer and Freeman [89] implemented a subjective study using a survey. The result showed that a wind farm has more impact on those people who live close to it and who are more familiar with the original landscape. Most people prefer to see wind turbines that are neutral toned, larger in size but small in utility quantity. Other surveys showed that the public usually supports wind power and the renewable energy industry [91]. However, most local residents may oppose construction of a new wind farm close to them, even though they know it will benefit the society. This neighborhood opposition to construction projects is the so-called Not-In-My-Back-Yard syndrome (NIMBY) [91,92]. The basic concept of the NIMBY syndrome is that people tend to support wind energy at a conceptual level, but concerns about unfavorable effects from wind farms cause people to be opposed to the implementation of local wind farm projects. However, the NIMBY syndrome, which has been widely used to explain public opposition to wind farms, was questioned by some scholars. Ek [93] found that people who are more interested in environmental issues are more likely to have a positive attitude towards a wind energy project. Erp [94] concluded that the attitudes of the developer, the local decision makers, and the decision processors have significant influence on public attitude towards a wind energy project. However, aesthetic concerns about wind turbines are legitimate and concrete. Torres-Sibille et al. [95] used an objective method to study the aesthetic impacts of wind farms. To measure wind farm induced visual impacts on landscapes, they developed an indicator that involved the visibility, the color, the fractality, and the continuity of a wind farm.

Factors influencing the intensity of visual impacts of wind turbines include scenic backgrounds, local topographies, and local landscapes between viewers and turbines [90]. When idle, a wind turbine looks like an abandoned machine. If a wind turbine is located near a scenic spot or an archaeological area, people are more likely to view the turbine as visual pollution. If a wind turbine is built in narrow or closed areas such as valleys, its visual impact appears to be more intensive [90]. A wind turbine located on a hill may induce direct visual impact, but intensity can be weakened when viewing from a higher elevated position [96]. Therefore during the selection of the site for a wind farm, areas with high perceived scenic quality, especially on the coast, should be avoided. A simulation study conducted by Bishop and Miller [97] showed that in all weather and visibility conditions, the visual impact intensity of wind turbines decreases when viewed from a greater distance. The study also showed that wind turbines have less intense negative visual effects when their blades are moving. Hurtado et al. [98] employed a 3D model to study the visual impact of wind farms on surrounding villages. The number of blades and the blade rotating directions of a wind turbine can influence its visual impact. According to Sun et al. [78], a wind turbine with three blades is more acceptable to people who are sensitive to visual impacts than the one with two blades. The reason could be that the turbines with three blades tend to give a stronger sense of balance. Wind turbines with counter-clockwise rotating blades generated stronger visual disturbance to viewers [78]. The wind turbine layout in a farm can be categorized into regular layout and irregular layout. Generally, the regular layout created a better sense of visual regularity and consistency than the irregular layout, which may lead to a sense of chaos. However, even with the regular layout such as a grid, the intensity of the visual impact may change as the viewer moves across the landscape and observes the turbines from different directions and elevations [99].

### 2.5. Reception of radio waves and weather radar

Although the electromagnetic field of a wind turbine itself is extremely weak and is confined in a small range [90], it can still create electromagnetic interferences. Bacon [100] found three degradation mechanisms that can interfere with waves: the near-field effects, the diffraction effects, and the reflection or scattering effects. Studies carried out by Randhawa and Rudd [101] showed that the diffraction in the Fresnel zone and the reflection or scattering effects created by wind turbines are the main mechanisms which degrade the radio performance. Wind turbine towers and blades can be an obstacle and can cause interference for wireless services. Wind turbine blades modulate radio wave signals strongly enough to affect many electromagnetic systems such as televisions, FM broadcast radios, microwave communication systems, and navigational systems [102]. This interference can induce ghosting effects (also named video distortion), which are pale shadows on a television screen. Interference also can cause errors in navigational systems and disrupt the modulation in typical microwaves. Wind turbines sometimes can create a shadow zone that blocks waves emitted from a transmitter [103]. They can also induce a diffraction effect with a predictable interference pattern around the turbine towers [101]. In addition, wind turbine towers sometimes can reflect radio waves because of reflective materials used on the towers. For instance, steel tubes for the turbine towers are good reflectors [103]. However, the blades of more recently constructed wind turbines are exclusively made of synthetic materials, which have minimized the impact on the transmission of electromagnetic radiation [90].

### 2.6. Climate change

Different studies have shown that wind turbines can impact local weather and regional climate. Zhou et al. [104] studied eight-year satellite data in regions of west-central Texas equipped with 2358 wind turbines and reported a temperature increase of 0.724 °C in the area. The study also showed that at night, the temperature increase was even more obvious. Wang and Prinn [105] demonstrated that, if 10% of global energy demand came from wind power in 2100, the global temperature would increase by 1 °C. Wind farms may also change the global distribution of rainfall and clouds. However, this warming effect caused by wind turbines is still much weaker than that generated by the emission of greenhouse gases on the global scale.

Research indicated that the recovery rate of the wind speed, after the wind passed through a wind farm, is a decreasing curve [106]. A modeling study showed that the impact of wind farms on the wind speed at the hub height was noticeable for at least 10 km along the downwind direction. This may be because of the extra roughness induced by wind farms [107]. The turbulence created by wind turbine blade rotations can affect the regional climate as well. Roy and Traitor [108] believed that the cooling effects during daytime and the warming effects at night for large wind farms are the direct results of the vertical air mixture near the ground surface. In a stable atmosphere where a warm air layer overlies a cool air layer, the vertical mixing can blow the warm air down and the cold air up, leading to a warm ground surface. On the other hand, in an unstable atmosphere with a negative lapse rate, the vertical mixing can push the cool air down and the warm air up, resulting in a cooling effect near the ground surface [108]. Therefore, wind farms altered the regional climate. This regional climate change can induce a long-term impact on wildlife and regional weather patterns.

In contrast, some other studies reported that wind farms were able to alleviate adverse climates, even though the effect was very limited [109]. Studies have found that the wind farms in Gansu Province of China were effective in decreasing the local wind speed and mitigated the hazards of sand storms [110]. Therefore, some researchers are studying the possibility of implementing intentional weather modifications by building giant wind farms [111].

Different analytical methods and models, such as the Blade Element Momentum model, the vortex wake method, and the computational fluid dynamics methods have been proposed for wind farm climate studies [112]. Barrie and Kirk-Davidoff [113] used the General Circulation Model to simulate wind farms as distributed surface roughness elements. Their analysis results showed that some atmospheric anomalies at the wind farm were the result of decreased wind speeds. Those anomalies grew quickly, along the downstream direction, in various forms of baroclinic and barotropic modes. Fiedler and Bukovsky [111] conducted a simulation study, using the nested regional climate model, on the effects of a giant wind farm on warm season precipitation in the eastern two-thirds territory of the U.S. This study used increased wind drag at the rotor height and the turbulent kinetic energy to parameterize the presence of wind farms rather than simply enhancing the ground surface roughness. A 1% increase in precipitation in 62 warm seasons was observed as the result of the presence of wind farms.

## 3. Mitigation of wind energy environmental risks

Wind farms may generate various environmental issues as reviewed in aforementioned literature. Those issues should be considered during the design and development phases of wind farms. Recent publications have explored public concerns about the negative effects of wind turbines [9,11]. Mitigation strategies are discussed in the following sections in order to involve more researchers and engineers in this campaign.

### 3.1. Limiting the effects on birds and bats

To reduce bird fatalities, several strategies could be considered. Restricting construction activities to non-breeding periods could help reduce the negative effects of bird disturbance [114]. Structural design improvements were also effective in reducing bird mortality [115]. For example, enlarging the blades and slowing the rotational speed of wind turbines can lower the bird fatality rate. The impact of wind turbines on birds' vision is one of the reasons why birds collide with turbine towers. McIsaac [116] found that the pattern-painted blades could increase the visual acuity of raptors. Blades can be more visible with night illuminations [15]. However, there are different opinions on what impact this solution would have. According to Langston and Pullan [25], the lights on turbine towers may attract birds, especially in bad weather conditions, and increase the chance of collision. However, Arnett et al. [46] found no difference in bird or bat fatalities at wind turbines, whether lit or not. A wind turbine that can automatically stop when birds approach could be very effective. De Lucas et al. [20] tested this idea, and the results showed that bird mortality decreased by 50% in a year while sacrificing energy production by 0.07%. Turbine design optimization is another effective way to reduce bat mortality [117,118]. Long et al. [119] proposed a methodology based on fundamental analytical models that optimizes turbine designs in order to maximize the chances of bats being able to detect the presence of the blades.

Site selection of a wind farm is also important [26]. The monitoring and modeling methodology proposed by Liechti et al. [120] is an effective approach to select a suitable location. The methodology suggested building wind farms far from important bird habitats and bird migration routes. It is helpful to work with ornithologists to consider possible impacts on birds when designing a wind farm layout. Bird flight activities in a zone of 200–500 m surrounding the planned wind farm should be recorded and analyzed [27]. Fight heights, directions, species, and behaviors of birds should be studied systematically. Sensitivity analyses are also helpful when selecting a wind farm location [121]. Clarke [122] pointed out that wind farms should be located at least 300 m away from any nature conservation site. Spatial distribution and aggregation activities of vulnerable species should be assessed before a wind farm construction in order to minimize bird disturbances [123]. After wind turbine locations are finalized, the direction of tower layout should be properly designed to reduce the effects on bird migration [124].

A suitable wind farm design is a comprehensive project [125]. Computer modeling and novel mapping techniques could be used to track the birds' migration routes when analyzing the potential effects of wind farms on bird conservation [27,126]. The spatial scale used in the modeling and mapping should be as large as possible [127]. Both short-term and cumulative impacts should be considered [128]. In addition to the computer modeling and mapping, field inspections and monitoring are also useful. Modern instruments such as video, radar, and acoustic and thermal imaging equipment have been successfully applied to study bat mortality under different weather conditions and in different landscapes [15]. Infra-red video cameras, as well as pressure and vibration sensors, have been integrated into automated recording systems to perform the environmental assessment of wind turbines and collect information on bird movements [12].

Northrup and Wittemyer [129] summarized the mitigation methodologies for the environmental impacts of wind turbines in their research. However, as Busch et al. [130] pointed out, in addition to the technical improvements, an international cooperative effort is important to reduce the environmental impacts due to global wind farm construction.

### 3.2. Reducing influence on marine environment and climate

To mitigate meteorological impacts of wind farms, the rotor-generated turbulences should be reduced [109]. Through improved rotor and blade designs and a proper design of turbine spacing and pattern, the turbulences can be mitigated, and the hydro-meteorological impacts can be reduced. It is also suggested to locate wind farms in regions where wind energy is abundant and the frictional dissipation is high. In this way, the wind energy will be harvested instead of losing as frictions. The purpose of this strategy is to increase the efficiency of wind farms [131].

Preliminary research showed that the noise caused by the offshore wind turbine operation could not be heard at 20 m below the water's surface [132]; studies also indicated that visual impacts of wind farms could be negligible at eight km away from the shore [132]. However, efforts are needed to further understand the influence of offshore wind turbines on the marine environment since the offshore wind farms are not always located far from the shoreline. With the increasing height of the wind turbine towers and the increasing size of the offshore wind farms, the environmental impacts of wind farms such as habitat fragmentations, noises, vibrations, electro-magnetic interferences, the impacts on fish, marine mammals and benthos are becoming significant. Therefore, the construction of offshore wind farms should be strictly managed to avoid ambient water pollution. Pile driving should not be conducted during the migrating seasons of porpoises to minimize disturbances. Through modeling and analysis, offshore wind farms should be spatially allocated to maximize revenues while protecting marine fish populations [133].

### 3.3. Noise reduction

To reduce noise from wind turbines, improved blade design is the key. A balance between the noise radiation and the energy production should be explored during the blade design phase [134]. An appropriate design of blades can significantly reduce the aerodynamic noise. The application of upwind turbines is also useful to reduce low frequency noise [135]. The insulations inside the turbine towers can effectively mitigate the mechanical noise during the course of operation [136]. The special gearboxes for wind turbines introduce less noise than standard industrial gearboxes. The steel wheels of the special gearbox have semi-soft and flexible cores with hard surfaces to ensure strength, to extend the lifetime of the equipment, and to muffle noise [137]. Direct drive wind turbines without any gearbox or high-speed mechanical component can operate more quietly. Variable-speed turbines create less noise at low wind speeds than the constant-speed turbines [135]. Besides technical measures, another way to avoid noise-induced problems is to build wind farms close to noisy areas. For example, road traffic can mask wind turbine noise if the traffic noise exceeds the turbine noise by at least 20 dBA. This method is effective for fairly quiet wind turbines with 35–40 dBA noise level [138]. Different criteria on the noise levels and the standoff distances between wind farms and habitations have been provided by different countries or regions. Suitable criteria should be followed with a comprehensive consideration of specific local conditions for a wind farm development.

### 3.4. Mitigating visual impact

The planning guidelines from the Ireland Department of the Environment, Heritage and Local Government (DEHLG)[32] suggested four factors to limit a wind farm's visual impacts on landscapes during the design phase: (1) whether it is acceptable to change the landscape; (2) how visually dominant are the wind turbines on the landscape; (3) what is the relationship between aesthetics and the wind energy development; and (4) how important is the impact. The shadow flicker issue from wind turbines can also be predicted and avoided with an appropriate sitting design of a wind farm.

To encourage local residents to have a positive perception of wind farms, public participation in the early stages of the planning and implementation of wind power projects are recommended, such as working together to seek solutions to the visual impact issues [88,93]. Early communication is crucial to avoid conflicts with the public [85]. Devine–Wright [139] suggested that a project should go beyond the NIMBY label and incorporate social and environmental psychological aspects. The ‘backyard’ motives are dominated by the feelings about equity and fairness rather than selfishness, and institutional factors can play a more important role than the public acceptance of wind power projects [85,140]. Involvement of local residents and good communication can help decrease the public resistance to wind energy projects.

Wind turbine tower layouts can be categorized as regular and irregular formats. Generally, the fewer the number of wind turbines and the simpler the layout, the easier it is to create a visually balanced, simple and consistent image. For regular landscapes such as an open or leveled space, a regular layout, such as a double line, a triangle, or a grid, is preferred. Irregular layouts are more suitable for the landscapes with variable elevations and patterns [141]. Selecting an appropriate color for a turbine is important to mitigate its visual impact. Rather than painting turbines in a color to camouflage them against their background, it is more suitable to choose a color to engage the turbines to the backdrops at different views and in different weather conditions [99]. White, off-white or light gray gives people a feeling of cleanliness and efficiency. Dark or metallic colors, typically for industrial elements, may not be suitable for wind turbines [31].

### 3.5. Reducing electromagnetic interference

In Greece, construction of wind farms within a certain distance of a telecommunication, radio, or television station is forbidden [136]. However, in other European countries, wind turbine towers are commonly used for the installation of antennas to improve communication services, such as mobile phone services [136]. With regards to the compatibility and interference with telecommunications, Binopoulos and Haviaropoulos [136] argued that the electromagnetic radiation and interference of wind turbines are very limited. However, there are scenarios when the electromagnetic interference causes problems. For these situations, various measures can be used to minimize the problem. Blades made from synthetic materials, compared to steel blades, produced less interference. Wind farms could be planned and constructed at locations without blocking broadcast signals [90]. The installation of extra transmitter masts could also be a solution, with a little extra cost for investors [90]. In regions where the wind turbine induced electromagnetic interference already occurred, deflectors or repeaters could be installed to overcome the problems.

## 4. Conclusions

Renewable energy is one solution for the global energy problem. In addition, renewable energy has beneficial socioeconomic impacts such as diversifying the energy supply, increasing regional and rural development opportunities, and creating domestic industry and employment opportunities [142]. However, renewable energy can create environmental issues in a habitat or a community. Even though the environmental impact of wind turbines is still a controversial topic, the impact should not be ignored. Minor issues today may cause disastrous effects in the future when wind energy becomes one of the main energy sources. As shown in this review study, more scientific studies are needed on the potential impacts of wind farms on the environment. Wind energy exploitation and related infrastructure construction projects should be evaluated for the economic, social, environmental, biological, and ecological influences. Suitable measures should be implemented to mitigate the environmental issues caused by the infrastructure construction and facility operation of wind farms. Developers, planners, and government officials need to gather and communicate complete information with the public to ensure that the projects are developed in a way that avoids, minimizes, and mitigates environmental impacts.

The paper reviewed published information regarding the environmental impacts of the wind power industry and the potential mitigation measures. Based on the discussions, several observations are summarized as follows:

(1) Various rates of bird and bat mortalities caused by the wind turbines have been reported in literature. Turbine types, the topographic feature of a wind farm, bird/bat species, climatic conditions, and many other variables affect the mortality rate. Although it is not clear how significantly offshore wind farms affect the marine environment, caution should be used when locating offshore wind turbines close to major habitats of local sea animals. Many countries still do not have specific bio-system protection standards against wind turbines. It is often the developer's responsibility to conduct the environmental impact study. Extensive research is still needed to fully understand the influences of wind farms on local biological systems.

(2) Noise induced by wind turbine operation has been studied for many years, and several criteria have been published in different countries and regions. One reasonable approach to reduce the noise disturbance of wind turbines is to follow suitable noise limits and distance criteria developed from those scientific studies. However, compared to the rigorous researches on other noise sources, such as transportation noise, there is not enough solid data and quantitative scientific studies about wind farm noises. More research is required to accumulate the knowledge of wind farm noises through field measurements and theoretical analyses.

(3) The visual impact of wind farms on the landscape is a subjective issue. Social studies and technology improvements could be used to help solve the problems. Even though disagreement remains about the meteorological impact and the electromagnetic interference of wind farms among different studies, large-scale wind farms do generate problems for regional climate and communication services. Therefore, mitigation technologies and measures at different scales should be considered during the wind farm planning stage.

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