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Impacts of wind energy on environment: A review

Shifeng Wang [a,*,1], Sicong Wang [b,1]

[a] Department of Architecture, University of Cambridge, 1-5 Scroope Terrace, Cambridge CB2 1PX, UK
[b] Department of Economics, Swansea University, Swansea SA2 8PP, UK

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ABSTRACT

Wind power is increasingly being used worldwide as an important contribution to renewable energy. The development of wind power may lead to unexpected environmental impacts. This paper systematically reviews the available evidence on the impacts of wind energy on environments in terms of noise pollution, bird and bat fatalities, greenhouse gas emissions, and land surface impacts. We conclude that wind energy has an important role to play in future energy generation, but more effort should be devoted to studying the overall environmental impacts of wind power, so that society can make informed decisions when weighing the advantages and disadvantages of particular wind power development.

Contents

1. Introduction

The dual challenges of climate change and energy security mean that renewable technologies are required in the future. Wind energy is considered to be an important source of renewable energy and has been used commercially to produce energy services in the United States (US) since the early 1980s. It has become an increasingly important sector of the renewable energy industry, and may help to satisfy a growing worldwide demand for electricity [1,2]. Wind power has been rapidly developed worldwide (Fig. 1) [3]. The European Union alone passed the 100 Gigawatts (GW) capacity in September 2012, while the US and China surpassed 50 GW and 50 GW in August 2012, respectively [4–6]. Worldwide, there are now over two hundred thousand wind turbines operating, with a total capacity of 282 GW at the end of 2012 and a global annual installed wind capacity of 44.71 GW in 2012 [3]. The average annual growth in new installations was 27.6% between 2005 and 2010 [3,7]. Based on current growth rates, the World Wind Energy Association (WWEA) [8] projects the global cumulative installed wind capacity to be 1,900 GW by the end of 2020. Wind power market penetration is expected to reach 8% by 2018 [9].

However, development of wind power could lead to unexpected environmental impacts on ecosystems, due to the many

* Corresponding author.
E-mail address: wangsf1013@gmail.com (S. Wang).
[1] Co-first authors.

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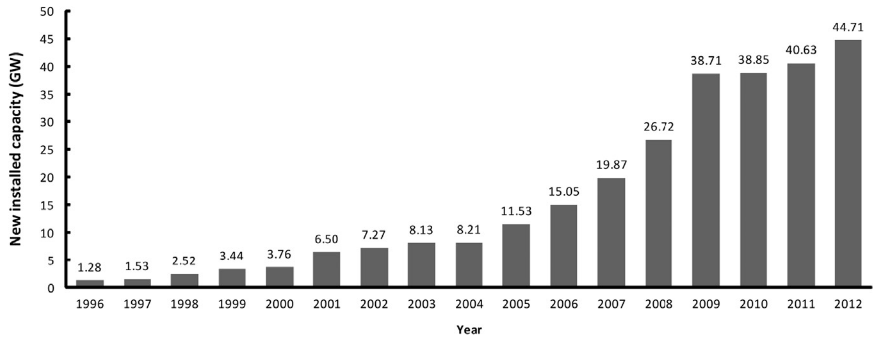

Fig. 1. Global annual installed wind capacity 1996–2012 [3].

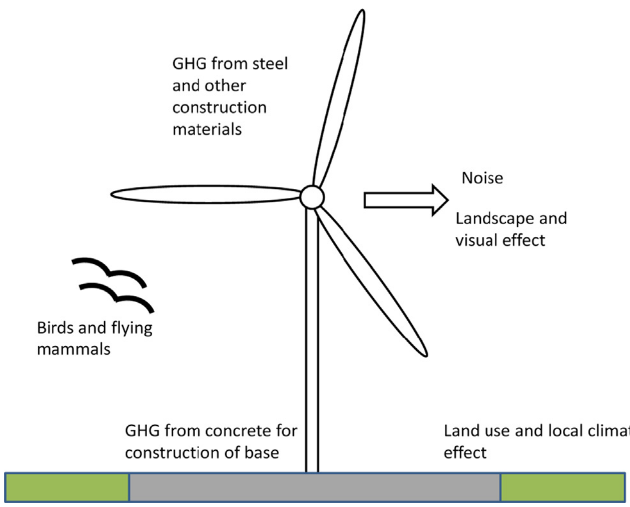

Fig. 2. Environmental impacts of wind power.

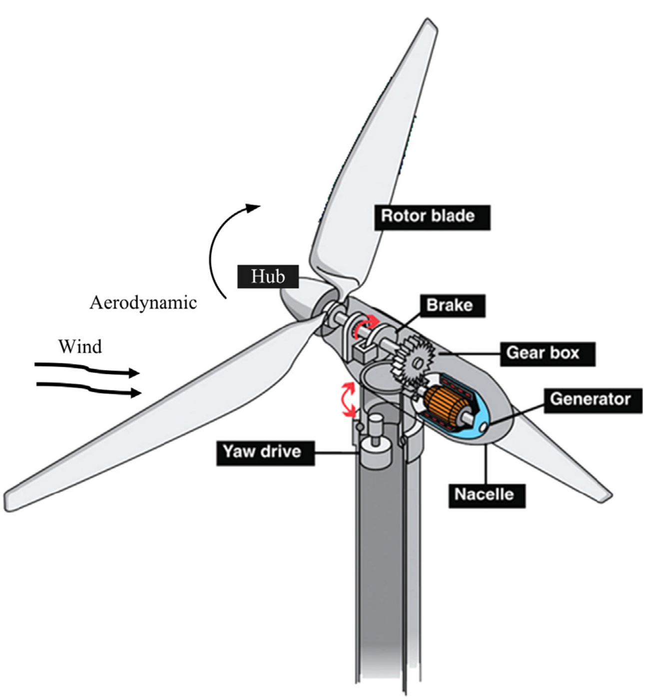

Fig. 3. Wind turbine noise sources. The mechanical noise includes the noise from hub, rotor blade, brake, gear box, generator, nacelle and yaw drive. The figure is adapted from Kunz et al. [2].

processes involved in the whole wind energy chain (raw materials procurement, construction, conversion to energy services, etc.) which will generate environmental impacts that affect the atmosphere, soil, water and living organisms. This review will collate information for use in the development of sustainable energy technologies and identify gaps in the study of environmental impacts of wind power as well as offer informative implications for policy makers. Noise pollution, bird and bat fatalities, greenhouse gas (GHG) emissions and local climate are the most significant environmental impacts, and are therefore the focus of this paper (Fig. 2).

2. Environmental impact assessment

The development of wind power will cause land use change and modify landscape settings, which will impact upon the living space, biological system and regional earth surface system, including noise pollution, bird and bat fatalities, GHGs and surface climate. Understanding these impacts will enable better mitigation and the creation of more effective renewable energy policies.

2.1. Noise pollution

Noise is defined as any unwanted sound. Wind turbines generate two types of noise: mechanical and aerodynamic. The mechanical noise is generated by the turbine's mechanical and electrical parts, while the aerodynamic noise is generated by the interaction of blades with the air (Fig. 3). The noise emission from wind turbine is a combination of both. Recently, due to the emergence of advanced mechanical design (e.g. proper insulation to prevent mechanical noise from proliferating outside the nacelle or tower, vibration damping), the mechanical noise has been reduced effectively, and is no longer considered to be as important as the aerodynamic noise, especially for utility scale wind turbines.

There are two main types of methods to measure the noise emissions from wind turbine. One is to use prediction models like semi-empirical models [10], and the other is to follow the international standards and/or International Environmental Agency (IEA) recommendations, with the help of devices such as IEA A-weighting. Recently, the prediction models have been more extensively developed. The most popular semi-empirical model is the one developed by Brooks et al. [11] which is derived by fitting a scaling law of Ffowcs Williams and Hall to the wind tunnel measurements of noise from two-dimensional NACA0012 aerofoil. However, the measurement of noise emissions from wind turbines is difficult: although several semi-empirical models have been designed, these models either are rather simplistic or make use of complex computational fluid dynamics solvers, and their application is rather time-consuming [10]; international standards and

Table 1
Bird fatality of wind power.

Region	Fatality	Reference
Vansycle Oregon-USA	10 fatalities per year	[21]
Klondike Oregon-USA	8 fatalities per year	[21]
Foot Creek Rim, Wyoming-USA	35 avian per year	[21]
West Virginia-USA	118 avian per year	[21]
Nine Canyon, Washington-USA	36 fatalities per year	[21]
Buffalo Ridge, Minnesota-USA	14 deaths per year	[21]
Four eastern states in the US	0.003% of anthropogenic bird deaths per year	[22]
Altamont Pass, California-USA	0.02 to 0.15 collisions per turbine per year	[23]
United States	440, 000 mortality per year	[24]
Navarra, Spain	0.1–0.6 collisions per turbine per year	[23]
Tarifa, Spain	0.02–0.15 collisions per turbine per year	[23]

guidelines about noise measurement have been designed for industrial sources, and are not always applicable to the measurement of noise emissions from wind turbines, mainly due to the fact that measurements are carried out in windy conditions (i.e. an issue outside the scope of standards dealing with noise measurements from industrial plants). The measurement of noise from wind turbines is influenced by the background noise (e.g. traffic on nearby roads and rail tracks). In many cases, it is difficult to measure sound pressure levels from modern wind turbines at wind speeds around 8 m s^{-1} or above, because the noise from the wind itself or background sounds may generally mask the turbine noise completely [12,13]. At lower wind speeds (e.g. 4–6 m s^{-1}) the noise from a wind turbine is more noticeable, since wind is strong enough to turn the blades but is not itself very noisy. Kaldellis et al. [10] reported that at 5.1 m s^{-1} wind speed at 10 m height, the noise from wind turbines was 48.5 $\pm$ 1.6 dB, approximately 9 dB more than the ambient sound.

Noise may have an effect on the fatality of species (see Subsection 2.3). Some bat species are known to orient toward distant audible sounds [14] and they could thereby be attracted to the sounds generated by the rotating blades, but there is no data to confirm this. Bats may also be attracted to the ultrasonic noise produced by wind turbines [15]. Observations using thermal infrared imaging suggest that bats do fly and feed in close proximity to wind turbines [2,16].

2.2. Bird fatality

Although wind power is generally considered environmentally friendly, the development of wind power has been associated with the death of birds colliding with turbines and other wind plant structures. Due to lack of understanding of the level of avian use at areas, some of early wind powers installations in the US caused relatively high risk of turbine collisions, because these facilities were located regions where birds were abundant [17]. Due to the development of standardized methods for siting wind power [18] and monitoring for avian impacts [19,20], many new developments have reduced the risk of turbine collisions. The bird fatalities range from 8–118 birds per year or 0.02–0.6 collisions per turbine per year (Table 1)[21–24]. Raptors are found being more susceptible than other species. The European Wind Energy Association (EWEA) [23] reported that raptors showed some of the highest levels of mortality in both Altamont Pass, California, and Tarifa, Spain; this is due to their dependence on thermals to gain altitude, to move between locations and to forage. Some of them are long-lived species with low reproductive rates and thus more vulnerable to loss of individuals by collisions. Raptors are most affected (78.2%) during spring, followed by migrant passerines during post-breeding migration (September/October) [23]. Other species reported include Eurasian griffon (*Cyps fulvus*), Kestrel (*Falco tinnunculus*), Short-toed eagle (*Circaetus gallicus*) and Black kite (*Milvus migrans*). Barrios and Rodriguez [25] reported that the fatalities for Eurasian griffon (*Cyps fulvus*) were 0.12 per turbine per year, 0.14 per turbine per year for Kestrel (*Falco tinnunculus*), 0.008 per turbine per year for Short-toed eagle (*Circaetus gallicus*) and 0.004 per turbine per year for Black kite (*Milvus migrans*), respectively. There is, however, uncertainty in bird fatality measurements which have to be adjusted upwards, as scavengers are known to remove bird carcasses before researchers could discover them and researchers may miss carcasses, especially in agricultural landscapes and dense forest ridge tops [26–28].

The avian mortalities of wind farms are very dependent on the season, weather, specific site (e.g. mountain ridge or migration route), topography, species (large and medium versus small, and migratory versus resident), type of bird activity (e.g. nocturnal migrations and movements from and to feeding areas), layout of the wind farm and type of wind technology [23,24,29]. The main factors which determine the mortality of birds by collision in wind farms include landscape topography, direction and strength of local winds, turbine design characteristics, and the specific spatial distribution of turbines on the location [23,29]. However, it is still unclear how these factors impact the avian mortalities of wind farm and therefore efforts to understanding these are still needed.

2.3. Bat fatality

Bats will be killed by wind farms, especially by utility-scale wind energy facilities. Bat fatalities are reported to be relatively small before 2001 [30]. This is largely because most monitoring studies are designed specifically for bird fatality assessment and therefore bat fatalities are likely underestimated [19,26]. Recent monitoring studies indicate that large numbers of bat fatalities have been observed at utility-scale wind energy facilities, especially along forested ridgetops in the eastern US [2,21,30–32], and in agricultural regions of southwester Alberta, Canada (Table 2) [32–49]. Similar bat fatalities have been reported at wind energy facilities in Europe [50]. The number of bats killed by wind energy facilities installed along forested ridgetops in the eastern US is reported ranging from 15.3 to 53.3 bats per MW per year, and the bat fatalities reported in southwester Alberta, Canada, are comparable to those found at wind energy facilities installed along the forested regions of the eastern US [2]. The bat fatalities at the Buffalo mountain site are reported as 53.3 bats per MW per year at 3 small (0.66 MW) Vestas V47 wind turbines (Vestas Wind Systems A/S, Ringkobing, Denmark) and 38.7 bats per MW per year at 15 larger (1.8 MW) Vestas V80 wind turbines [32]. The bat fatalities at Lewis County, New York, are estimated ranging from 12.3 bats to 17.8 bats per MW per year at 1.65 MW Vestas wind turbines, depending on carcass search frequency [41]. Bat fatalities from regions of the western and mid-western US are relatively

Table 2
Bat fatality of wind power, modified from Kunz et al. [2].

Region	Fatality (MW^{-1} $year^{-1}$)	Reference
Buffalo Mountain, TN I-USA	31.5	[33]
Buffalo Mountain, TN II-USA	41.1	[32]
Buffalo Mountain with small Vestas V47 wind turbines-USA	53.3	[32]
Buffalo Mountain with large Vestas V80 wind turbines-USA	38.7	[32]
Buffalo Ridge, MN I-USA	0.8	[34]
Buffalo Ridge, MN II (1996–1999)–USA	2.5	[35]
Buffalo Ridge, MN II (2001–2002)–USA	2.9	[36]
Foote Creek Rim, WY-USA	2.0	[37,38]
High Winds, CA-USA	2.0	[39]
Klondike, OR-USA	0.8	[40]
Lewis County, New York-USA	12.3–17.8	[41]
Lincoln, WI-USA	6.5	[42]
Meyersdale, PA-USA	15.3	[43]
Mountaineer, WV (2003)–USA	32.0	[44]
Mountaineer, WV (2004)–USA	25.3	[43]
Nine Canyon, WA-USA	2.5	[45]
Oklahoma Wind Energy centre, OK-USA	0.8	[46]
Stateline, OR/WA-USA	1.7	[47]
Top of Iowa, IA-USA	8.6	[48]
Vansycle, OR-USA	1.1	[49]
Southwestern Alberta, Canada	15.3–41.1	[2]

low, ranging from 0.8 to 8.6 bats per MW per year. This could be because many of these studies were designed only to assess bird fatalities [19]. Like bird fatalities, bat fatalities may be underestimated, since scavengers can remove carcasses before researchers are able to recover them [26].

Bat fatalities of wind power vary not only with location, topography, layout of the wind farm and type of wind technology, but also with species and other factors. Bat species that migrate long distance are those most commonly killed at utility-scale wind energy facilities in the US [2]. In North America, foliage-roosting, eastern red bats (*Lasiurus borealis*), hoary bats (*Lasiurus cinereus*) and tree cavity-dwelling silver-haired bats (*Lasionycteris noctivagans*), each of which migrate long distances, are identified at wind energy facilities [2]. Other bat species killed by wind turbine in the US include the western red bat (*Lasiurus blossivilli*), Seminole bat (*Lasiurus seminolus*), eastern pipistrelle (*Perimyotis* [=*Pipistrellus*] *subflavus*), little brown myotis (*Myotis lucifugus*), northern long-eared myotis (*Myotis septentrionalis*), long-eared myotis (*Myotis evotis*), big brown bat (*Eptesicus fuscus*), and Brazilian free-tailed bat (*Tadarida brasiliensis*) [2].

Bats are struck and killed by the turning rotor blades of wind turbines, and the factors increasing risk include the increasing height of wind turbines, the modifications of landscapes during installation of wind energy facilities, including the construction of roads and power-line corridors and removal of trees to create clearings, the sound produced by wind turbines (though no evidence), the complex electromagnetic fields in the vicinity of nacelles produced by wind turbines, and weather conditions like low wind speed at night [2]. It is, however, unclear why these factors increase the risk to bats. Potential explanations include: (1). The increase in height of wind turbine enlarges the danger area for bat and therefore increases the possibility of a bat, who migrates or forages at higher altitudes, touching the wind blades. (2). The modifications of landscapes may attract more bats around wind turbines, due to the creation of favourable environment for aerial insects upon which most insectivorous bats feed. (3). Some bats may be acoustically oriented or disoriented. (4). Some bats use receptors to guide fly. The complex electromagnetic field produced by wind turbines will interfere with perception in receptors. (5). The weather conditions such as cool and foggy conditions in valleys may make bats active along ridgetops, which will increase the likelihood of striking the moving wind turbine blades.

2.4. Greenhouse Gas Emissions

Wind power mitigates GHG emissions if the energy produced displaces fossil fuels, but some GHGs are also emitted; most of which arise from the production of concrete and steel for wind turbine foundations. Life-cycle analysis (LCA) is always used to assess the life-cycle GHG emissions from wind power, because it takes into account the whole life from-cradle-to-grave (i.e. from raw material extraction through material processing to disposal or recycling). The LCA shows that the GHG emissions from wind power range from 2 to 86 g CO_2e/kW h (Table 3) [51–56]. The large variability in the estimation of GHG emissions is mainly due to the size of wind farm, the methods used to estimate GHG emissions from the life cycle of wind farm, and locations. For example, Wiedmann et al. [52] reported that the life-cycle GHG emissions from 2 MW wind turbine were 13.4 g CO_2e/kW h using a process-based LCA, 28.7 g CO_2e/kW h using an integrated hybrid LCA (which linked the inputs of goods to processes to technology matrix derived from financial transactions between economic sectors) and 29.7 g CO_2e/kW h using an InputOutput-based hybrid LCA approach (which approximated the actual input requirements of the desired wind power subsector by using information from process analysis). In this estimation, the two hybrid LCAs produce higher figures than the process-based LCA. This is because the process-based LCA truncates inputs from higher upstream production processes when setting the system boundaries.

2.5. Land surface impacts

When wind turbines operate, they generate turbulence in their wakes. The turbulence is small-scale, chaotic almost-random air movement and will modify the vertical mixing of lower and upper level air. The modification of vertical mixing of lower and upper level air has different impacts on the regional land surface for during the day and at night. The turbulence wakes mix cool air down and warm air up during the day, and mix warm air down and cool air up at night. This raises the surface temperature at night, but may have no significant impact on surface temperature during the day, because during the day the large daytime mixing due to solar heating offsets the cooling produced by turbulent. The modification of vertical mixing of lower and upper level air may impact the cloud formation and hence the local precipitation.

Table 3
GHG emissions from wind power with LCA.

Wind farm size	GHG emissions [g CO_2e/kW h]	Reference
250 W wind turbine	46.4	[51]
2 MW wind turbine	28.7	[52]
2 MW wind turbine	13.4	[52]
2 MW wind turbine	29.7	[52]
2 MW wind turbine	6.6	[53]
4.5 MW wind turbine	15.8	[51]
Wind turbines in Brazil and Germany	2–81	[54]
Offshore wind power in coastal Germany	45	[54]
–	15–25	[55]
–	9.7–123.7	[56]

Therefore, while converting wind's kinetic energy into electricity, wind turbines modify surface-atmosphere exchanges and the transfer of energy, momentum, mass and moisture within the atmosphere (Fig. 4). These changes may have noticeable impacts on local to regional weather and climate if spatially large enough. Observations with satellite data shows a significant warming trend of up to 0.72 °C per decade, particularly at night-time, over wind farms relative to nearby non-wind-farm regions [57]. However, studies for the impacts of wind power on land surface exchanges are relatively new, and better effort to understand these impacts is needed.

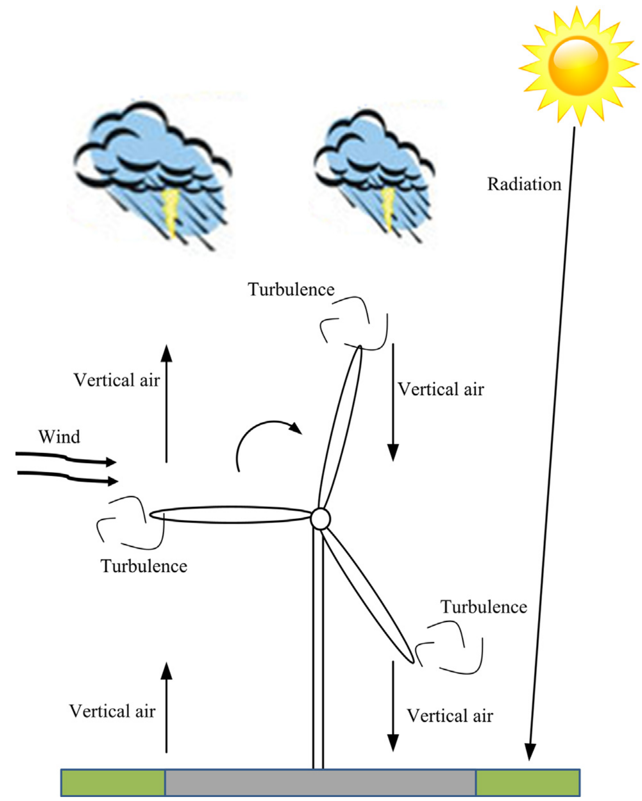

Fig. 4. Physical processes between wind power and surface-atmosphere.

3. Discussion

Wind power is regarded as a promising renewable energy, and is growing rapidly worldwide. However, the deployment of wind power depends to a considerable degree on its environmental performance, and needs critical consideration. Although the deployment of wind power does cause noise emissions, the noise emissions from wind farm are smaller than those from city traffic (Table 4) [58]. Noise emissions of wind farm can be further reduced through design of wind turbines, and careful location and planning of wind farms.

The bird fatality resulting from wind power is also rather small. Evidences show that it is smaller than other energy industries, or other-made structures such as power lines, in the US (Table 5) [24,59,60]. Such small bird fatality would not cause the serious loss of the richness of species, at global and local scales. However, there is no assessment for the overall environmental impacts of wind power, and comparisons between wind power and other energy technologies, such as fuel, are rare, but would be of great benefit to policy makers.

Generating electricity from wind energy reduces the consumption of fossil fuels, and therefore results in GHG emission savings. A study conducted by Irish national grid found that the reductions in CO_2 emissions, due to fossil fuel displacement by wind energy, range from 0.36 to 0.59 t CO_2 per MW h [61]. GWEC [62] reports that the 97 GW of wind energy capacity installed at the end of 2007 will save 122 million tonnes of CO_2 every year, helping to combat climate change. Embedded GHG in turbine construction is therefore very small compared to the GHG mitigated through fossil fuel displacement. Carbon payback times on mineral soils can be extremely short, though the payback time on peatlands can be longer due to the carbon potentially lost from the peats during construction [63,64].

While the deployment of wind power will produce lower noise pollution levels than other ambient noises of human activity, generate far lower bird and bat fatalities than other human activities, and mitigate the GHG emissions, it may

Table 4
Comparative noise for common activities [58].

Source/activity	Indicative noise level (dB)
Threshold of hearing	0
Rural night-time background	20–40
Quiet bedroom	35
Wind farm at 350 m	35–45
Busy road at 5 km	35–45
Car at 65 km/h at 100 m	55
Busy general office	60
Conversation	60
Truck at 50 km/h at 100 m	65
City traffic	90
Pneumatic drill at 7 m	95
Jet aircraft at 250 m	105
Threshold of pain	140

generate noticeable impacts on local to regional weather and climate if the area of turbines is large enough. The noticeable impacts may offset the benefits from the lower noise pollution levels, lower bird and bat fatalities, and mitigation of GHG emissions. This again calls for overall assessment of environmental impacts of wind power. Therefore, before the large deployment of wind power, more monitoring experiments, specifically for the overall assessment of environmental impacts, are still needed, in order to obtain the sustainable desirable renewable energy sources. The monitoring experiments should be designed to take into account the location, layout and size of wind farm, and type of wind technologies.

The environmental impacts of wind power will interact each other. For example, noise may have an effect on the fatality of species. However, the mechanism of interaction among these impacts is still unclear. Due to this, the review for the interaction among these impacts is excludes. Nevertheless, understanding the

Table 5
Avian mortality in the United States.

Item	Estimated mortality per year (in thousands)	Reference
Wind turbines	440	[24]
Aircraft	80	[59]
Nuclear powerplants	330	[24]
Large Communications Towers (over 180′, North America)	6,800	[60]
Communication towers (cellular, radio, microwave)	4,000–50,000	[24]
Fossil fuel powerplants	14,000	[24]
Cars and trucks	50,000–100,000	[24]
Agriculture	67,000	[24]
Pesticide use	72,000	[24]
Building windows	97,000–976,000	[24]
Domestic cats	100,000	[24]
Hunting	100,000	[24]
Feral cats	110,000	[24]
Transmission lines (conventional powerplants)	175,000	[24]

mechanism of interaction among these impacts will contribute to mitigate the adverse environmental impacts of wind power, and would be an interesting topic in the future research.

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