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Environmental aspects of the potential development of wind energy in forested areas in Poland

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Abstract. The impact of wind power installations on the natural environment, including forest ecosystems, has been investigated for a considerable period of time. Based on currently available data, the authors conclude that operating wind turbines within forest areas poses a significant threat to forest environments, particularly to flying animals, including legally protected species. The reviewed studies indicate that wind power plants situated in forests have substantial potential to affect both the natural environment and the landscape. It has been found that siting wind farms in forested areas, which are typically characterised by high biodiversity, further increases the environmental risks commonly associated with such installations. Locating wind energy facilities in forests has also generated social controversy in countries where such investments are being implemented, primarily in Germany and the Scandinavian countries, and is frequently opposed by environmental protection organisations and scientific experts. In their conclusions, the authors state that although lower procedural costs and the anticipated greater ease of obtaining permits for publicly owned land may encourage investors to plan such developments in forest areas, the confirmed higher environmental costs – compared with constructing wind turbines in open landscapes – necessitate a critical assessment of the justification for such investments.

Keywords: Forests, wind turbines, renewable energy, environmental impact, birds, bats, climate

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1. Introduction

Wind energy is one of the key elements of the energy transition in Europe. At present, electricity generation from wind is an important component of the energy sector in Poland, accounting in August 2025 for 28.5% of the installed capacity of renewable energy, which itself represented almost 49% of the total installed capacity of the Polish power sector (Rynekelektryczny.pl 2025; ARE n.d.). The share of wind power plants in the national energy mix in 2024 was 14.7% (Copernic n.d.). Electricity generation using wind is also planned as a fundamental component of the future energy mix alongside nuclear power plants (Ministerstwo Klimatu i Środowiska 2021).

According to a report by the European Environmental Bureau (EEB), Poland will require approximately 0.8% of the country's total area by 2030, and approximately 1.8% by 2040, in order to accommodate sufficient solar and wind capacity needed for decarbonisation. At present, this issue remains within the scope of political decisions by the Polish authorities (Ministerstwo Klimatu i Środowiska 2024).

Wind energy, as a non-emitting source of energy, is regarded as a solution that contributes, during its operation, to environmental protection, particularly climate protection (Kim, Park 2023; Osman et al. 2023). However, any technological solution introduced without appropriate precautionary measures may pose a threat to the natural environment, irrespective of prior pro-environmental assumptions. For this reason, at the planning stage of energy investments, the balance of environmental benefits and losses is assessed and environmental impact assessments (EIAs) are carried out, as in the case of other activities involving interference with nature.

The issue of constructing wind power plants in forest areas is not new, and in some European countries, especially in Scandinavia and Germany, considerable practical experience already exists. Consequently, numerous studies have been produced presenting research results on the impact of wind turbines on forest environments (Sorkhabi et al. 2016; Bunzel et al. 2019; Gaultier et al. 2020; Balotari-Chiebao et al. 2021; Schöll, Nopp-Mayr 2021). These studies have shown that wind power plants located in forests have substantial potential to affect the natural environment and landscape. As a result, this practice has long given rise to public controversy and has frequently met with opposition from environmental protection organisations and scientific experts. However, in some countries, for example in Scandinavia, the availability of open areas meeting distance requirements is limited, while the anticipated greater ease and lower cost of procedures on public land may encourage investors to plan such projects in forest areas, particularly those belonging to the State Treasury or local authorities.

Wind energy infrastructure, including wind turbines and wind farms, may adversely affect the landscape, the abiotic, biotic (including human), and social environment (Pohl et al. 2012; Kokologos et al. 2014; Anshelm, Simon 2016). Because of the potential for conflicts both with the natural environment and with human neighbourhoods, wind power plants are typically erected in open areas, away from places that are particularly sensitive to their direct impact. Construction is most often regulated by strict guidelines, and for specific locations it is necessary to obtain confirmation that the environmental impact of the project will be no more than minor. One of the aims of this procedure is to mitigate significant damage to the natural environment. These procedures also apply to such investments located in forests. Numerous scientific studies have confirmed that wind power plants may pose a threat to bats and birds at local, regional and supra-regional scales.

The primary factors through which the construction and operation of turbines affect the forest environment are changes in the spatial structure of the forest, including the potential destruction of sites occupied by plants, fungi and animals belonging to protected or rare species, resulting from the construction and location of turbines within the forest. Subsequently, the operation of such investments entails direct losses, including the killing of flying animals by operating rotors and disturbance of the behaviour of both flying and terrestrial animals caused by noise, as well as various indirect effects (Laranjeiro et al. 2018; Katzner et al. 2019; Dhar et al. 2020). Birds and bats are considered groups particularly vulnerable to the adverse effects of wind turbines, which affect them in various ways (Voigt et al. 2012; Laranjeiro et al. 2018). These factors are often cited as the reasons for existing public opposition to wind energy (Enevoldsen, Sovacool 2016).

The aim our paper is to provide a detailed review of as many existing studies as possible concerning the impact of the construction and operation of wind turbines on forest environments, especially in the temperate zone, to assess the problem, and on this basis to formulate conclusions that may be useful when making potential decisions on investment in wind energy in forest areas.

2. Effects of wind turbines on selected elements of the forest environment

2.1. Effects on bats

Most studies have found that bats are the most numerous fatal victims of wind energy, exceeding birds in this respect (Köppel et al. 2014; Schuster et al. 2015; Thaxter et al. 2017). All bat species in Poland and throughout the European Union are subject to strict species protection, and many of them are threatened. At the same time, this group of animals has been the subject of particularly numerous studies, which have repeatedly shown that the adverse effects of wind energy on bats are strongly dependent on turbine location and increase considerably, among other factors, as the distance between turbines and the forest edge decreases.

Bats sustain lethal and near-lethal injuries as a result of collisions with rotating blades or as a result of pressure trauma (barotrauma), caused by a sudden drop in pressure near the moving edge of the rotor (Baerwald et al. 2008; Szoldatits et al. 2012; Dai et al. 2015; Jones et al. 2015; Schuster et al. 2015; Thompson et al. 2017; Gaultier et al. 2020).

In Central and north-western Europe, the species dominating turbine collision statistics are the common pipistrelle (*Pipistrellus pipistrellus*), Nathusius' pipistrelle (*P. nathusii*) and the noctule bat (*Nyctalus noctula*), which, together with five other species, accounted for 98% of all bat fatalities (Gaultier et al. 2020). Seven of the eight species mentioned are significantly associated with forest environments, while all forage mainly in open space, between and above tree canopy.

Bats occur at high densities in forested areas and potentially fly higher than, for example, in agricultural areas, which increases their exposure to collisions with rotor blades (Reusch et al. 2022). Where bat migration occurs above forests, turbines located there may kill these animals more frequently during migration periods than turbines in open areas. This results, among other things, from the greater height of turbines erected in forests, while migratory flights of some species in stronger winds, when turbines are operating, take place several hundred metres above ground level (Lagerveld et al. 2024). Another reason is the greater activity of some species above forests during migration. During seasonal migrations, bats do not rely on fat reserves alone, but stop to forage intensively in food-rich places, including ecotonal zones at the boundaries of forest areas (Šuba et al. 2012; Hurme et al. 2025).

In the temperate zone of the Northern Hemisphere, mortality of migratory bats at wind farms is highest in late summer and autumn, with a second, lower peak during early spring migration (Cryan et al. 2014; Dai et al. 2015; Schuster et al. 2015; Thompson et al. 2017; Laranjeiro et al. 2018; Gaultier et al. 2020; Browning et al. 2021; Rnjak et al. 2023). This applies particularly to forested hills and mountain ridges (Thaxter et al. 2017; Wang, Wang 2015), along which migration may occur or which may serve as stopover sites, and which, owing to more favourable wind conditions, may at the same time be considered attractive locations for potential energy investments. In the temperate climatic zone of Europe, bat mortality from collisions with wind turbines located in forests usually ranges, depending on location, from 4.0 to 41.1 individuals/turbine/year (2.3–22.8 individuals/MW/year), and in only one case out of ten farms was no mortality recorded, which does not necessarily mean that mortality was absent; the issue of detectability is discussed further below. By comparison, for turbines located on pastures, mortality was 0.0–13.6 individuals/turbine/year (0.0–16.0 individuals/MW/year, with no mortality recorded in half of the cases), while on arable land it was 0.0–5.3 individuals/turbine/year (0.0–9.4 individuals/MW/year, with no mortality recorded at 10 of 24 farms) (Rydell et al. 2010). It follows that bat mortality in forests may be expected to be several times higher than on arable land or non-forested wasteland.

The siting of a wind turbine directly within a forested area causes specific changes in the spatial structure of the environment. These consist in the creation of an additional edge area, or ecotone, between the forest and an open area, namely the deforested surroundings of the

Table 1. Level of collision risk with wind turbines (excluding microturbines and small wind turbines) for European and Mediterranean bat species covered by the EUROBATS guidelines (state of knowledge: September 2014) (Rodrigues et al. 2014)

High risk	Medium risk	Low risk	Unknown risk
***Nyctalus* spp.**	***Eptesicus* spp.**	***Myotis* spp.****	***Rousettus aegyptiacus***
Pipistrellus spp.	*Barbastella* spp.	*Plecotus* spp.	*Taphozous nudiventris*
Vespertilio murinus	*Myotis dasycneme**	*Rhinolophus* spp.	*Otonycteris hemprichii*
Hypsugo savii			*Miniopterus pallidus*
Miniopterus schreibersii			
Tadarida teniotis			

"*= in areas rich in water bodies. ** = exclusively *Myotis dasycneme* in areas rich in water bodies"

Table 2. Potential negative impacts of wind power plants on bats at different stages of the investment process and during different phenological periods (After: Kepel et al. 2013, based on Rodrigues et al., 2017, supplemented)

Kind of influence	Pregnancy and lactation (VI–VII)	Spring (IV–V) and autumn (VIII–X) migrations	Autumn swarming (VIII–X)*	Hibernation (XI–III)
During the construction period				
Loss of bat foraging sites and flight routes to feeding grounds during the construction of access roads and wind turbines (felling trees, filling water bodies)	Low or moderate impact (and exceptionally – high), depending on the species or site	Probably minor	Low or moderate impact (and exceptionally – high), depending on the site	Minor or no impact
Loss of roosting sites during the construction of access roads and turbines (felling trees, demolition of buildings, filling entrances to underground structures)	Probably high or very high, depending on the species and site	Locally high or very high (e.g. loss of mating sites)	Probably high or very high	Probably high or very high
During the turbine operation period				
Emission of sounds of various frequencies (disturbance/scaring of bats)	Impact probably limited or absent	Impact probably limited or absent	Impact probably limited or absent	Probably no impact
Loss of foraging sites due to bats abandoning the area	Moderate (and exceptionally – high)	Probably minor in spring, moderate or (exceptionally) high in autumn	Not applicable	Minor or no impact
Loss or alteration of flight routes (migration corridors)	Moderate	Minor	Minor or moderate	Minor or no impact
Mortality resulting from collisions with operating rotors or from pressure-related injuries (barotrauma)	Minor, moderate, or high impact, depending on the bat species (Table 1)	Most often high or very high	With regard to flight routes to swarming sites, the impact is moderate	Minor or no impact

*mainly concerns Myotis bats *Myotis* spp., long-eared bats *Plecotus* spp., and the western barbastelle *Barbastella barbastellus* turbine, as well as the creation of forest-edge habitat along the service road and transmission line. The threat to fauna arises from the fact that ecotones and open areas within forests are the main areas of activity for forest bats and birds, while forest roads, like other linear landscape features, are typical movement routes for these animals (Verboom, Huitema 1997). In this situation, the structural changes listed above will result in an increased density of flying animals in the immediate vicinity of each wind turbine, which will inevitably lead to increased mortality (Ellerbrok et al. 2023). In forests in Germany, confirmed bat mortality did not fall below 3.8 individuals/turbine/year, reaching a maximum of 41.1 (Rydell et al. 2010). In studies conducted in Saxony, turbines located 0–100 m from the forest edge killed significantly more bats than those located farther away (Seiche et al. 2008). Similarly, Rydell et al. (2010), in a study of 37 European wind farms, found a significant positive correlation between the percentage of woodland cover in the vicinity of wind turbines and bat mortality. It should be emphasised that the factors listed above also mean that the results of pre-construction monitoring for investments in forest areas will, by definition, be particularly unreliable, since the subsequent presence of constructed facilities and the associated environmental changes will significantly affect the activity of the animals being monitored.

Another factor increasing the threat posed to bats by wind energy facilities in forests is the attraction of insects to their vicinity, caused by a local rise in temperature in the deforested area and by the erection of a tall structure in that place, namely the turbine tower; many insects swarm around the tallest object in a given area, the so-called hilltopping effect. Such conditions have been shown to attract flying insects (Cryan et al. 2014; Millon et al. 2015), which in turn attracts foraging bats. Bats foraging in open spaces may also treat turbine towers as tall trees, seeking orientation points or resting places during autumn migration (Kunz et al. 2007; Cryan, Barclay 2009; Barclay et al. 2014; Jameson, Willis 2014). Recent research conducted in Germany on a sample of 22 turbines at six locations over three years (Knörnschild 2024) showed increased mating, as well as foraging, activity of bats in the immediate vicinity of turbine towers. The researchers found that the tall tower structures of wind turbines attracted bats, which used them like the tallest trees in the surrounding landscape. This concerned bat species regarded as particularly vulnerable to mortality in collisions with wind power plants, chiefly the noctule bat and Nathusius' pipistrelle (Knörnschild 2024). Other studies in Germany have shown that the increase in activity of bats hunting in open space and at high altitude, such as noctules, around erected wind turbines is particularly pronounced in forested areas (Ellerbrok et al. 2022).

As indicated above, the impact of wind turbines operating in forests differs among bat species. Ellerbrok et al. (2022) indicate that bat mortality caused by rotors is selective, posing the greatest threat to fast- and high-flying bats, as well as to long-distance migrants (McKay et al. 2024). Apoznański et al. (2018) report that the western barbastelle *B. barbastellus*, which in Poland is a bat mainly inhabiting forests, is a relatively rare victim of wind turbines, but this occurs when turbines are located at considerable distances from the species' core habitats. Some other bats, which fly slowly and low, by contrast avoid the vicinity of wind farms, probably deterred by noise and disturbed airflow. This is a second potential factor, besides killing by rotors, in the impoverishment of forest bat assemblages in areas where wind farms operate. Species potentially threatened by this type of impact include both bats hunting among tree crowns, in the understorey and on the ground, which use passive hearing that is exceptionally sensitive to noise when detecting prey, such as the greater mouse-eared bat *Myotis myotis*, Bechstein's bat *M. bechsteinii* and long-eared bats *Plecotus* spp., and species catching prey in the air at the boundary between tree crowns and the open space above them, such as the barbastelle *B. barbastellus*. The conservation status of the species listed here is high: all except long-eared bats are included in Annex II of the Habitats Directive, and some are also included in the European and global Red Lists of threatened species under the NT or VU categories. Studies show that in collisions with turbines located in open areas these species are killed only sporadically (Rydell et al. 2010), and thus until now they have largely remained free from the potentially adverse effects of wind energy. However, after the introduction of wind turbines into forested areas, an expansion of the spectrum of harmful anthropogenic impacts onto their populations can be expected. Research covering 24 forest complexes in Germany demonstrated a statistically significant decrease in the activity, and therefore occurrence, of bat species hunting at low heights and among tree canopies in the vicinity of operating wind turbines. This activity decreased by as much as half, and the effect was observed at distances of several hundred metres from the turbine (Ellerbrok et al. 2022). Habitat loss in bats due to disturbance has until now been an overlooked element in assessing the impact of wind energy on these mammals, which was justified in open spaces that do not constitute attractive foraging habitats for the species in question. The displacement effect may also, up to a point, limit the impact of the factor on population status; for example, Green et al. (2021) found no decline in the abundance of migratory silver-haired bats *Lasionycteris noctivagans,* despite the presence of wind turbines along the migration route. Nevertheless, even then, habitat loss finally could affect population status. In north-western France, a 51% reduction in the activity of species gleaning prey from vegetation, namely mouse-eared bats and long-eared bats, was recorded, but significant declines in activity were also observed in species hunting in open space but roosting during the day exclusively in forests: Leisler's bats *Nyctalus leisleri*, by 19%, as well as the threatened and highly protected barbastelle. The authors of these studies suggest that European guidelines, including EUROBATS and many national guidelines, recommending that wind turbines be located at least 200 m from the forest edge in order to reduce bat mortality, still seriously underestimate the effect of habitat loss for these animals; moreover, in the analysed region of France, 89% of turbines did not comply with these guidelines (Barré et al. 2018).

The methods usually used for pre-construction bat surveys for the purpose of assessing the impact of planned wind power plants on this group of mammals, based mainly on acoustic monitoring, may be of limited effectiveness. For example, the activity of the noctule bat, one of the species most vulnerable to fatal collisions, recorded at ground level using an ultrasound detector in mature stands, remains low or very low, significantly lower than in clear-cuts or open areas (Rachwald 1992; Węgiel et al. 2019). This is understandable in light of knowledge of the ecology and behaviour of this species: it is adapted to hunting at high altitude and far from obstacles, in open space, rather than inside forests. However, open space also extends above tree crowns. Radiotelemetry studies show that the most preferred foraging habitats of noctule bats are, almost equally, pastures and forests (Mackie, Racey 2007). At present, in environmental impact assessments for wind investments, the practical possibility of widespread use of methods alternative to ground-based acoustic monitoring is considerably limited. Large-scale use of radiotelemetry in studies of bird and bat activity, or large-scale installation of stationary ultrasound detectors in tree crowns, is expensive and time-consuming. Consequently, the potential mortality risk to species that are less effectively surveyed using standard monitoring methodology may be underestimated. It may be argued that commonly adopted monitoring methods are not fully adapted to studying the species most vulnerable to the adverse effects of turbines in forest areas.

The latest studies by Hurme et al. (2025) also indicate that noctule bats do not migrate along fixed migration corridors. Their flight routes depend on the random configuration of atmospheric fronts used by the animals to assist their flights. Between sudden movements, individuals of this species stop to replenish energy through intensive foraging, largely in random locations that may occur in different areas each year. There they seek temporary day roosts and the richest foraging grounds. Consequently, pre-construction surveys carried out in a given year do not necessarily produce results representative of subsequent years. For this reason, it is appropriate to apply the precautionary principle and to assume that areas particularly attractive in terms of shelter availability and foraging resources, such as forests, constitute sites of particularly high collision risk between noctule bats and turbines during migration, even if this risk varies in intensity between years.

Similarly, post-construction monitoring in forest areas detects the actual impact of turbines less effectively than in open areas. This results from the much lower detectability of killed bats and from difficulties in observation and acoustic surveys in such terrain. Owing to its spatial structure, forest, compared with open areas, is difficult to observe and search, and finding dead animals is highly problematic. The surroundings of wind turbines located in forests, including the stand and understorey, constitute a serious obstacle to assessing bat, and also bird, mortality caused by operating wind turbines. Fatal victims of collisions with turbines with high rotor hub heights (which are the only turbines installed in forests) may also fall outside the search area and consequently be entirely missed or impossible to detect (Weber et al. 2018). In addition, significantly faster removal of dead or injured bats and birds by predators and scavengers can be likely expected in forests. This calls into question the effectiveness of accepted methods for monitoring environmental impacts in the case of wind turbines located in forested areas. Alternative research methods to carcass searches, such as thermal imaging and optical observations, are very difficult in forested terrain and, moreover, sufficiently expensive and labour-intensive that their use is currently rational only on an experimental scale, with limited spatial and temporal samples. It is now accepted that currently available data, which indicate high bat mortality caused by wind turbines in forests, are nonetheless underestimated and that actual mortality is even higher.

The current state of knowledge on the particularly negative impact of wind turbines located in forests on bats is also reflected in current guidelines on minimising the environmental impacts of wind energy. The negative impact of turbines in forest locations has been studied and confirmed, while pre-construction monitoring does not allow the precise scale of this impact to be predicted, as shown above. Among methods for preventing or reducing this impact, the most common is turbine curtailment at low wind speeds, which should to some extent reduce the threat to bats. However, the application of this method in forests will also be less effective because of the aforementioned limitations in the effectiveness of both pre- and post-construction monitoring. For this reason, existing studies and guidelines recommend avoiding the siting of wind turbines in forests and their vicinity.

The guidelines developed by the Agreement on the Conservation of Populations of European Bats, EUROBATS, of which Poland is a member and signatory, state with regard to the siting of wind turbines near forest areas that such facilities should be located at a minimum distance of 200 metres from the forest edge, with this distance measured from the outer reach of the rotor blades (Rodrigues et al. 2014). Furthermore, a resolution adopted by the Meeting of the Parties to EUROBATS, including Poland, points to the need to take into account that habitats and areas where a negative impact of investments on bats is expected may not be suitable for the construction and operation of wind turbines (EUROBATS 2022). Forested areas meet precisely the definition of such areas. This resolution calls on the Parties to the Agreement to comply with the guidelines referred to above.

A similar position is found in the 2013 Guidelines for assessing the impact of wind power plants on bats, prepared on behalf of the General Directorate for Environmental Protection in Poland (Kepel et al. 2013). Although these guidelines have not been officially recommended, they are widely used by investors and enforced by environmental protection authorities in Poland when assessing the environmental impact of planned wind investments. Together with the EUROBATS guidelines, they constitute an indicator of the state of contemporary knowledge within the meaning of Article 52(1) and Article 68(1) of the Act of 3 October 2008 on the provision of information on the environment and its protection, public participation in environmental protection and environmental impact assessments (Ustawa 2008). The European Commission guidelines on wind energy development and EU nature legislation (European Commission 2020) also draw attention in several places to the increased risk associated with locating wind turbines in forest areas, particularly for bats.

2.2. Effects on other mammals

It has also been found that some terrestrial mammals, including cervids, hares, martens and wolves – the list remains open, as further studies are being conducted both in Europe and on other continents – either avoid areas of operating and under-construction wind farms (Łopucki et al. 2017; Kati et al. 2021; Schöll, Nopp-Mayr 2021; Chowdhury et al. 2022; Kumara et al. 2022; Tolvanen et al. 2023), or show symptoms of chronic stress, such as the badger *Meles meles* and the common vole *Microtus arvalis* (Agnew et al. 2016; Łopucki et al. 2018), or modify behavioural patterns, as in the European hamster *Cricetus cricetus* (Łopucki, Perzanowski 2022). The displacement or withdrawal of one or more species under the influence of the presence of wind turbines may have direct consequences for other species because of cascading effects (Thaker et al. 2018). In forest areas, the impact on terrestrial mammals may be greater than in open areas because these animals generally occur more frequently in forests. This applies to most large native mammals, including game species, such as the red deer *Cervus elaphus* and wild boar *Sus scrofa*, and protected species, including the Eurasian lynx *Lynx lynx*, wolf *Canis lupus* and brown bear *Ursus arctos*. If wind farms were to constitute a barrier to the movement of lynx and wolves, as some data suggest (Marques et al. 2018), this could also pose a threat to the continuity of their populations.

2.3. Effects on birds

Birds are, after bats, the second most numerous group of vertebrates that may be affected by wind turbines through direct mortality. In this case, death results from in-flight collisions with elements of wind turbines and associated infrastructure. It should be noted, however, that other impacts also occur, manifesting as physical, ecological and behavioural effects. This also applies to forest environments; for example, avoidance of turbine vicinity has also been recorded in some birds which, because they mainly remain beneath the canopy of trees or shrubs, such as robins *Erithacus rubecula*, are relatively infrequent victims of collisions with turbine blades (Gibson et al. 2017). A meta-analysis by Tolvanen et al. (2023), covering 66 peer-reviewed publications on the impact of wind turbines on birds, showed that in 63% of the most numerous species were found to abandon their territories in the vicinity of turbines. This applies to a considerable extent to forest species. For example, studies of tawny owls *Strix aluco* in Spain (López-Peinado et al. 2020) and eagle owls *Bubo bubo* in Norway (Husby, Pearson 2022) indicate that the radius of the so-called exclusion area for these species exceeds 5 km from the turbine; birds move from such areas to more distant sites. Ongoing studies at several wind farms located in forests in eastern Germany indicate that the zone of complete exclusion around turbines for all owl species exceeds 1 km and is usually larger (Wylegała et al., unpublished data). It is assumed that three factors contribute to this. Noise caused by turbines prevents hunting by hearing, areas around turbines become poorer hunting grounds, and direct killing of owls through collisions with rotor blades is an additional factor. In Europe, it is forest-associated owl species that die most frequently. Among victims in both Germany (Dürr 2023a) and other European countries (Dürr 2023b), the eagle owl predominates, followed by the long-eared owl *Asio otus*. It has also been found that noise caused by turbines within a radius of more than 800 m reduces time devoted to breeding and the breeding success rate of the capercaillie *Tetrao urogallus* (Taubmann et al. 2021). Near wind investments, this species showed a population decline due to reduced habitat suitability (González et al. 2016), and there was no indication that adaptation to altered acoustic conditions had occurred eight years after the turbines became operational (Coppes et al. 2020).

The impact on birds concerns a significantly larger number of species than in the case of bats, including taxa for which even a very small increase in mortality may have a significant negative effect on favourable conservation status. In the Northern Hemisphere, passerines most frequently collide with wind turbines, accounting for 60–80% of avian victims (Zimmerling et al. 2013; Erickson et al. 2014), but the greatest threat to biodiversity conservation is posed by collisions involving large-bodied, long-lived birds with low reproductive rates, in particular raptors, but also, for example, waders, shorebirds, owls and cuckoos (Thaxter et al. 2017; Schippers et al. 2020; Schöll, Nopp-Mayr 2021).

Raptors are a group particularly vulnerable to the adverse effects

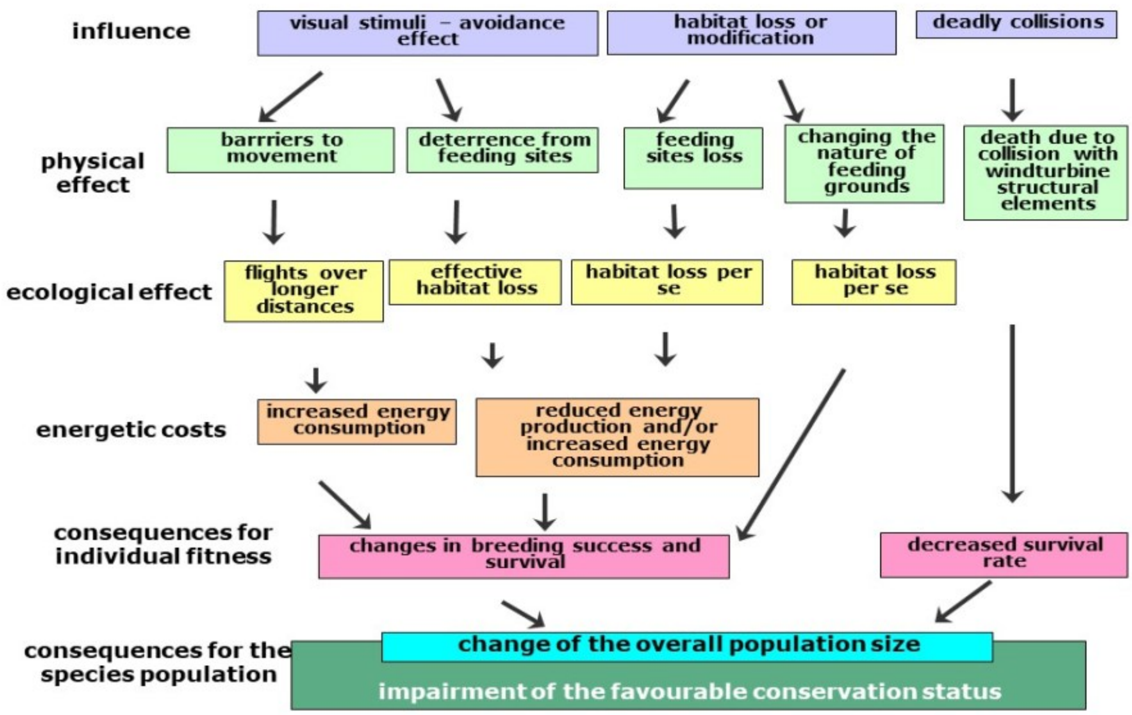

Figure 1. Schematic of the pathways of wind farm impacts on birds (Langston et al. 2006, supplemented)
Image source: Langston RHW, Fox AD, Drewitt A 2006. Conference plenary discussion, conclusions and recommendations. Ibis 148, Suppl. 1: 210– 216.

of wind turbines, including species with collision rates disproportionately high in relation to their abundance, such as the red kite *Milvus milvus*, white-tailed eagle *Haliaeetus albicilla*, lesser spotted eagle *Clanga pomarina*, common buzzard *Buteo buteo*, golden eagle *Aquila chrysaetos* and common kestrel *Falco tinnunculus*. At the same time, owing to their demographic characteristics, even a small number of collision victims among species in this group translates into noticeable declines in population growth rates (Schippers et al. 2020), resulting in threats to the persistence of local or regional populations (Schaub 2012; Bellebaum et al. 2013; Cervantes et al. 2022; Estellés-Domingo, López-López 2024). A significant proportion of these species nest in forests and wooded areas, and it is there that protection zones around their nests are established. Locating wind turbines in forest areas will therefore increase the risk of fatal collisions directly at breeding sites, probably to a greater extent than turbines located in open areas used by these birds as foraging grounds or during seasonal migration. This is confirmed by studies conducted in Germany, where the location of wind farms in forests has been permitted.

Average bird mortality resulting from collisions with wind turbines is estimated at 5–8 individuals/turbine/year (Chylarecki et al. 2011; Loss et al. 2013; Zimmerling et al. 2013), or 3–5 individuals/MW/year (Loss et al. 2013; Erickson et al. 2014; AWWI 2019), or even 11 individuals/MW/year (Smallwood 2013), with very high variability between locations and individual turbines. Recent studies suggest that these estimates may be almost threefold underestimates (Smallwood et al. 2020). The collision risk for birds, as for bats, increases with turbine height and installed capacity (Loss et al. 2013; Huso et al. 2021; Garvin et al. 2024). Consequently, replacing old turbines with new-generation, higher-capacity turbines does not necessarily, contrary to commonly promoted views, lead to a reduction in total bird and bat mortality (Huso et al. 2021). As noted earlier, detecting bird collisions with turbines in wooded areas, as in the case of bats, is significantly more difficult, and therefore results concerning the scale of impact in forests are likely to be considerably more underestimated and subject to greater measurement uncertainty than in open areas.

2.4. Effects on the microclimate of the forest ecosystem

The operation of wind turbines in forests, in addition to direct losses in the form of animals killed or deterred, may also cause more general environmental effects, including climatic effects (Wang, Wang 2015; Katzner et al. 2019; Hamed, Alshare 2022). Experience to date from other countries suggests that even when attempts are made to minimise impacts as far as possible and when ‘good practices’ are applied (Tucci 2017), locating turbines in forests is associated with localised but landscape-significant deforestation causing permanent forest fragmentation. It has been found that deforestation of a fragment of land combined with wind turbine operation causes changes in air circulation and increases evaporation in the vicinity of the turbine (Baidya Roy et al. 2004; Luo et al. 2021; Msigwa et al. 2022; Wang et al. 2023). In the longer term, this may cause unfavourable changes in parts of the forest adjacent to the turbine, especially in a situation where water shortage is already becoming an increasingly serious problem for forests. The long-term consequences of such impacts are difficult to estimate, which also means that they cannot be disregarded. In addition, the construction of turbine foundations, owing to deep excavations, may cause drainage of the adjacent area at least during the construction stage, as in the case of any major construction project carried out in a forest area.

The gaps in the stand that arise around the turbine also constitute a permanent exposure of the ground inside the forest. In addition, linear infrastructure elements, such as technical roads, typically with ditches draining rainwater, and power lines, are led to each turbine. Situations in which existing infrastructure can be used for this purpose without modification are exceptional. The construction or adaptation of infrastructure is also associated with permanent deforestation, drainage, changes in soil cover and forest fragmentation. This has ecosystem effects related primarily to rapid changes in the forest microclimate (Davies-Colley et al. 2000; Didham, Ewers 2014), accelerated thermophilisation (Zellweger et al. 2020; Govaert et al. 2021), and an increased edge effect around the gap, which has a particularly negative impact on so-called forest interior organisms. Minimising this effect requires a forest patch at least four stand heights wide (Sławski 2008), which means that around each turbine site approximately 0.8 to 1 ha of forest becomes an ecosystem open to external influences. These elements become both ecological barriers for small animals, especially invertebrates (Muñoz et al. 2015; Cardoso et al. 2020), and pathways for the invasion of alien species entering forest ecosystems along anthropogenic features (Flory 2006; Mortensen 2009; Foxcroft et al. 2011; Meunier, Lavoie 2012; Deeley, Petrovskaya 2022). Regular turbine maintenance and potential failures of transmission networks cause disturbances associated with vehicle traffic and the need for earthworks; their negative impact inside forests is significantly greater than in open agricultural landscapes. The impact of wind investments on forest ecosystems should also be considered in the context of increased forest fire risk, mainly through drainage and increased access resulting from the construction of access roads, as well as possible failures of infrastructure and of the turbines themselves. Under current climate change conditions, failures of overhead power lines are expected to constitute an important factor initiating forest fires (Mitchell 2013; Vahedi et al. 2025).

3. Summary

The purpose of this publication is not to analyse the legal status associated with the construction of wind turbines in forested areas, but to focus on assessing the potential impact on the natural environment on the basis of currently available sources. Undoubtedly, increasing the possibility of locating investments in treeless open areas on land would be beneficial both for the energy sector and for the natural environment. This would undermine the rationale for using forest areas for this purpose, as such areas are usually more valuable both in terms of natural environment and in terms of their influence on climate.

Understanding the full consequences of energy production is necessary for meeting energy demand in a stable, science-based manner. This should take place while simultaneously protecting ecosystems and human communities during a sustainable energy transition. In a period of increasing threats to the natural environment, including threats to forest persistence, opening up another potential threat to the forest environment by introducing a new factor that is controversial both socially and ecologically raises doubts. Every construction investment constitutes interference with the state of nature in the area where it is implemented. In the case of renewable energy investments, the fundamental issue is to assess the balance between losses to nature and the environmental benefits resulting from the construction of further facilities: wind turbines, solar power plants or hydroelectric power plants. It is widely accepted that the natural cost of constructing wind turbines in open areas is acceptable in view of the environmental benefits brought by the clean energy obtained in this way. In the authors' opinion, presented in this article on the basis of an analysis of available sources of knowledge, constructing such facilities in forest areas raises environmental costs to a higher level, which calls for a thorough assessment of the justification for such investments.

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Author contributions

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