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Critical Review

Bats and Wind Farms: The Role and Importance of the Baltic Sea Countries in the European Context of Power Transition and Biodiversity Conservation

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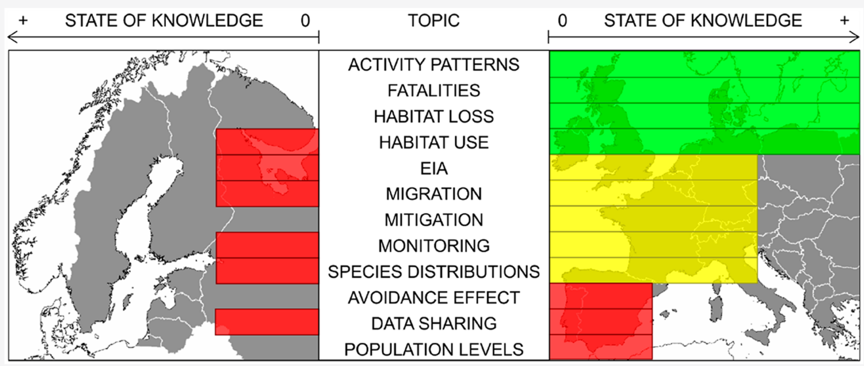

ABSTRACT: Although labeled as environmentally friendly, wind power can have negative impacts on the environment, such as habitat destruction or wildlife fatalities. Considering the distribution and migratory characteristics of European bats, the negative effects of wind power should be addressed on an appropriate scale. This review summarizes the current state of knowledge on interactions between wind farms and bats in Europe, and compares it with the situation in the countries of the European boreal biogeographic region. We analyzed data from papers published in international and national scientific journals, focusing on studies conducted in Europe. The issue of the impacts wind power has on bats is clearly overlooked in most of the countries of the European boreal region, with low volumes of research available on the topic. This is probably due to fewer wind farms in the area, making this recent issue a less-prioritized topic. However, the Baltic Sea, and the countries surrounding it, are of extreme importance with regards to bat migration, especially for the *Pipistrellus nathusii*. Therefore, more research on wind power and bats is needed in this region, as well as more cooperation between all the stakeholders.

1. INTRODUCTION

Wind power is a valuable asset for energy transition as it is an efficient and sustainable way of producing energy.[1,2] Moreover, it generates near-zero greenhouse gas emissions during its operation in contrast to fossil fuels, and the approximate payback time for wind turbines in Europe is only a few months.[3,4] However, wind farms can have negative impacts on biodiversity, by destroying habitats during the construction phase and causing bird and bat mortality during the operating phase.[5,6] Bats (order: Chiroptera) are already facing numerous threats worldwide, and given their low reproductive output, it is vital to consider them in wind power development.[7,8]

Despite the first observations of wind turbines causing bat mortalities dating back to 1972,[9] serious questioning of the impacts of wind power on this taxa only emerged at the end of the twentieth century, with increasing observations of dead bats at wind farms.[10,11] Before this period, consideration of bats in wind farm projects was not mandatory, partly because of a general lack of knowledge on bats; thus, farms were constructed in areas that now would be considered inappropriate because of an associated high collision risk for bats. Research has now produced hundreds of studies, articles, and books on the phenomenon and its characteristics to help understand the impacts of wind farms on bats, and creating effective mitigation for current and future wind power.[12−18]

Our understanding of the topic is mainly based on studies from Central Europe and North America.[7,19] However, there is

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Figure 1. European boreal biogeographic region (light gray area). Our studied area comprises the parts of Estonia, Finland, Latvia, Lithuania, Russia, and Sweden located in the boreal region and close to the Baltic Sea. The main migration flyways of bats are represented by black arrows. The dashed arrow indicates uncertainty about the use of the flyway. As an example, current (dark gray triangles) and future (light gray triangles) wind farm projects in Finland are presented.

little knowledge on the impact of wind farms on bats in the European boreal biogeographic region, a part of the continent significantly different from Central Europe (Figure 1). Conditions vary with latitude but generally this region possesses shorter summers, less light, lower temperatures and precipitation, and a longer snow cover than the rest of Europe.[20,21] The European boreal biogeographic region is mostly covered by forests (60% of the area) or wetlands (8% in average, but it reaches 50% in the northern part of the region).[21]

All the characteristics of this biogeographic region centered around the Baltic Sea also influence animal communities and their ecology, including bats.[19,22,23] It also means that interactions between bats and wind turbines may differ, with impacts varying in nature or intensity.

While the countries of the Baltic Sea region currently only have a small number of operational wind turbines, more projects have been initiated in order to reach the objectives in renewable energy production.[24] For instance, while there were only approximately 700 wind turbines in Finland by the end of 2019, there were also 211 ongoing projects for the construction of 3296 additional wind turbines, according to the Finnish Wind Power Association.

Despite the differences between these two parts of Europe, bat communities on the continent share undeniable and clear similarities. First of all, species present in the boreal region are also found in other parts of Europe. Second, several of these species, such as *Pipistrellus nathusii*, are long-distance migrants breeding in the boreal region during summer before reaching southern areas for wintering. The negative impacts that wind power has on bats seem to be similar in essence both in the Baltic Sea region and the rest of the Europe, but their characteristics vary. For instance, the species and guilds of bats found dead at wind farms are alike, however, their abundances differ. Additionally, all the countries represented here—excepted Russia—are members of the European Union (EU), meaning they share common policies and objectives regarding species conservation and wind power development. These features make comparing these two parts of Europe more relevant than comparing the European boreal biogeographic region with other parts of the world under the same boreal conditions such as North America where species, impact features, and policies are different. The Baltic Sea region has a unique situation, with the presence of important migratory flyways and breeding territories for EU-protected bat species, but where wind power and research on bats are still emerging. Therefore, improving both sustainable energy production and biodiversity conservation is a challenge for the involved countries, but could be achieved by investing in new research on the impacts of wind power.

For this review, we only considered countries characterized by their proximity to the Baltic Sea and having their territory partially or totally in the European boreal biogeographic region: Estonia, Finland, Latvia, Lithuania, Russia, and Sweden. We excluded Norway, as it has no territory around the Baltic Sea, and only included parts of Russia that are in the vicinity of the Baltic Sea (Figure 1).

This review summarizes the current knowledge on impacts and mitigation used in the Baltic Sea region and Central Europe. Within the current context of wind power, we

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identified several topics that need to be addressed by researchers, professionals, and authorities to help plan and develop wind power and bat conservation in a way that is beneficial to both.

2. IMPACTS OF WIND FARMS ON BATS IN EUROPE

The impacts of wind farms on bats vary in nature and duration, and can occur at all stages from the construction to the dismantling phase. The first impact to possibly take place is the loss of habitat and the following changes in bat fauna during the construction phase of a wind farm. However, the fatalities observed during the operating time of a farm are the most visible impact.[18] Furthermore, among the newly investigated topics in this field is the avoidance of operating wind farms and their vicinity by bats, which could severely affect species in Europe by decreasing their habitats' availability.[25]

We start by presenting the situation in Europe, then in the Baltic Sea region. For both contexts, analysis is organized according to the different impacts bats can face: fatalities, habitat loss, and disturbance.

2.1. Current Knowledge of the Impacts on Bat Fauna in Europe.

Fatalities. The characteristics of collisions with operating turbines have been extensively studied in Europe, at least in its western part. Fatalities occur mainly during autumn migration, roughly from August to mid-September[5,12,18,26] and a smaller peak can also occur during spring migration in certain parts of Europe.[12] The exact timing of fatalities varies latitudinally. For instance, in Southern Europe the period of higher collision risk is longer.[27,28]

Collision risk is primarily influenced by the location of a wind farm.[29,30] Indeed, farms located at certain landscape features such as coastlines, hill tops, or large rivers have been associated with higher rates of mortality,[29,31−33] as bats are known to use these linear features for navigation, especially during migration. Weather conditions also affect collision risk: nights with low wind speed, relatively warm temperatures, and no precipitation are associated with the highest collision risk.[12,34,35] In North America, it has been observed that large-scale weather phenomena, such as high pressure areas and low humidity, were more accurate in predicting collisions than local weather conditions.[36]

The species with the highest collision numbers in Europe are *Pipistrellus pipistrellus*, *Pipistrellus nathusii*, and *Nyctalus noctula*. However, this finding is derived mainly from Central Europe.[37] In total, there are eight species that account for 98% of all the dead bats found at wind turbines in northwestern Europe,[12] and these are defined as "high-risk species" because they face a higher probability of colliding with the turbines. In addition to the three aforementioned species, the high-risk species include *Vespertilio murinus*, *Eptesicus nilssonii*, *Pipistrellus pygmaeus*, *Nyctalus leisleri*, and *Eptesicus serotinus*.[19] Other species or species groups such as the *Myotis* spp. and *Rhinolophus* spp. are rarely found dead at wind turbines.[37] Species that are the most prone to collisions are predominantly aerial hawkers with wings and echolocation calls adapted for movement in open space: they are species that hunt on flying prey, usually far from the ground or any structures.[17,38] In turn, the low-risk species such as *Myotis* spp. and *Rhinolophus* spp. hunt close to surfaces or directly in the vegetation, which decreases the time that they spend in the rotor sweep zone, and further reduces the probability of colliding with the turbines.[12] Despite the earlier belief that only migratory bats were affected by collisions,[36,39] it was discovered that both resident and migratory species are prone to collisions with wind turbines throughout Europe.[10,28,40]

Individuals are either killed by direct collision (blunt-force trauma) with the moving blades or by barotrauma (tissue damage provoked by rapid pressure change) when flying close to the blades.[41,42] There is no record of bats killed by nonoperating wind turbines.[36] Barotrauma is difficult to account for as it does not always instantly kill injured bats, thus allowing for the possibility that the individuals might fly away; consequently, it may not be possible to find the carcass and include it in the fatality report.

The reasons for bat presence in the vicinity of wind turbines have also been investigated, with the initial hypothesis that collisions between bats and turbines are random.[17] Another hypothesis suggests that bats are at a greater risk of collision while expressing certain behaviors, such as flying high while migrating or hunting migratory insects.[41,43] Finally, there is also a hypothesis that turbines could attract bats into their vicinity.[41,44] The main reason for this attraction appears to be the presence of great numbers of prey insects close to the turbines, lured by the turbine's color and heat emission.[43,45,46] Another reason might be that bats are drawn to tall structures, which are easy to perceive in the landscape and which they confuse with large trees. Further, the exploration of wind turbines for roosting possibilities by bats,[39] or their utilization as social and mating sites,[47,48] have also been proposed to explain the presence of bats nearby turbines, but so far, they have still not been examined in detail. It is important to keep in mind that the relative importance of each factor attracting bats to wind turbines fluctuates depending on the considered species, the sex and age of the individuals, the time of year, or the location of the wind turbines (Figure 2).[43,49]

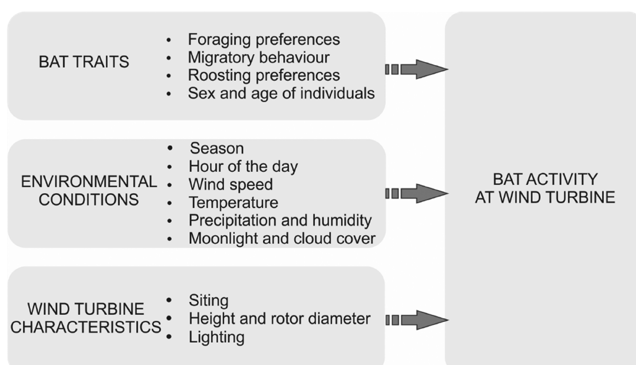

Figure 2. Parameters considered to influence the activity of bats close to wind turbines. The importance of each parameter is situation- and species-specific and can vary considerably.

Habitat Loss. Besides direct fatalities, bats also face the loss of habitat that can occur during the construction of a wind farm. This does not only include the construction of the turbines, but also the access roads, pads, power lines, and temporary or permanent buildings. Forest clearing or hedgerow destruction can affect the roosting, commuting, and foraging of several species; it can decrease the attractiveness of certain habitats, preventing individuals from reaching previously connected areas or lengthening the distances needed to reach these areas.[33,50] The bat species extensively using woodland for commuting and foraging, such as *Myotis* spp., are the most impacted by habitat fragmentation and destruction, in opposition to open-space foragers species,

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such as *Pipistrellus nathusii*, which are less dependent on landscape features for their daily movement and feeding.[51,52]

Disturbance. Construction and decommissioning steps often lead to several types of disturbance such as noise, vibration, light pollution, and to a general turmoil at the sites.[31] These disturbances can affect all bats when they are roosting[53] or hibernating,[54] but some species can also be impacted during commuting[55] or foraging.[56]

Once the turbines are built and in operation, there is still a risk of affecting the surrounding bats. Using ultrasonic detectors to monitor bat calls, a decreasing acoustic activity by the bats was recorded in France along hedgerows as the distance to the wind turbines was reducing.[25] Although this is not a recent discovery,[57] investigations on the issue only began a few years ago with other studies in Europe showing similar results at small[58,59] and industrial wind turbines.[44,57,60] This avoidance effect seems to affect most of the bat species, groups and guilds in a large radius, including gleaner bats and other species that are generally not considered sensitive to collision.[25] While a similar effect has been shown elsewhere in the world,[61] the consequences in Europe would be exacerbated if a similar effect was discovered in other landscapes and regions of the continent. No study has investigated the reason for such avoidance behavior, but the presence of lights and noise was proposed as a reason for bats shunning the area surrounding turbines.[25] It has also been suggested that bats avoid wind turbines because moving blades produce low-quality reflections of echolocation calls, and therefore are a navigational hazard for bats.[58,59] Another possibility is that wind turbines produce noise, and that bats tend to avoid noisy environments.[56] Nevertheless, it is currently impossible to confirm or disconfirm these hypotheses without more research on the topic.

2.2. Current Knowledge of Impacts on Bat Fauna Around the Baltic Sea. *Fatalities.* Data about fatalities in the Baltic Sea region are mainly coming from two sources: postconstruction monitoring reports and scientific studies. The monitoring reports are describing results of carcass searches and bat acoustic activity monitoring in wind farms. In Europe, among other missions, the EUROBATS organization compiles all the reports available to establish observed and estimated bat fatalities.[37] Thanks to this, there are records of bat fatalities in Estonia, Finland, Latvia, and Sweden. This means that wind farms in these countries have an impact on bats. The current numbers of collisions cannot, however, be compared to Central Europe because only a limited number of carcass searches have so far been conducted in the Baltic Sea region.

Postconstruction monitoring related to bats is not mandatory in Finland and is not often required by the environmental authorities. Nevertheless, some have already been conducted for research purposes or on behalf of the energy companies.[62,63] These led to the discovery of six *Eptesicus nilssonii* in 2012, but since then no additional mortalities have been reported according to EUROBATS.[37] This most likely reflects the lack of monitoring effort.

In Finland, in addition to postconstruction monitoring studies, only three scientific studies have been conducted on the impacts of wind farms on bats. In addition to finding two dead bats, the main conclusion of the first study was that EUROBATS guidelines could not be used in Finland because of the very different conditions, such as a tall and dense vegetation cover around turbines, and therefore specific guidelines should be developed; however, this has not been the case up until now.[62] The second study assessed the presence of bats at rotor height in southern Finland, including the migratory species *Pipistrellus nathusii* and the resident *Eptesicus nilssonii*.[64] The third research focused on migration of *Pipistrellus nathusii* along the Finnish western coastline, arguing that its aggregating presence during the migration period would clash with future establishment of wind turbines in the region (Figure 1), while sedentary species *Eptesicus nilssonii* should be taken into account for inland projects.[65]

In Estonia, only three bat carcasses have been discovered in a postconstruction survey in 2009 despite the expansion of wind farm constructions and no use of mitigation in the country.[66]

Lithuania has not released any fatality numbers yet, despite mandatory postconstruction monitoring since 2010, and the monitoring of about one-third of the wind farms in the country in 2015.[67] The first postconstruction monitoring in Latvia was conducted in 2013, leading to findings of 40 dead bats, including 23 *Pipistrellus nathusii* and 13 *Eptesicus nilssonii* at six wind farms.[68] Since then, either no additional survey has been conducted, or the data have not been shared.[69] We did not find any peer-reviewed studies conducted in these countries on the impacts of wind power on bats.

Russian wind power presence in the region is limited to three farms, with a total of five turbines. There are no data on the presence of bats at these turbines, but it is likely that their impact is very low or nonexistent.[67] However, one farm is located on the coast close to Kaliningrad[70] and could have some effect on migrating bats, because it is on the main migratory flyway of *Pipistrellus nathusii*.[71] But the potential impact of this wind farm on bats has not been studied yet.

For the Baltic Sea region, Sweden has the most data on bat fatalities because postconstruction monitoring is more common. By the end of 2015, about 22 monitoring programs had been conducted in Southern Sweden, most of them (16) including carcass searches. However, none provided good estimates of fatality rates at wind farms in the country because of an insufficient number of repeats or a lack of measures for scavenger removal, observer efficiency or investigated surface area.[19] Therefore, it is impossible to determine whether Swedish wind farms have a very low fatality rate or if the low quality of searches is leading to a clear underestimation of the actual numbers.[19] Ongoing studies along the coast of Southern Sweden are expected to give better estimates in the future, with the first results providing a fatality rate similar to German wind farms, around 10−12 bats killed per turbine per year.[19]

The situation in Northern Sweden is similar to Finland: basic information on the impacts of wind power on bats is missing. Only a single study was conducted to survey bat activity at wind farms, with no activity at rotor height but the presence of bats near the turbines.[72] The monitoring was also restricted to the use of four acoustic detectors on two different turbines at only one wind farm.[72] This is worrying because most new Swedish wind farms will be built in this region of the country in the future.[19]

There are only a few peer-reviewed studies on the impacts of wind power on bats in Sweden, and they mostly come from Southern Sweden.[10,40,43,46] Initially research focused on fatalities, as they are the most evident impact of wind farms. All species found were aerial-hawking foragers,[10] a pattern also true for the rest of Europe.[12] The presence of bats around wind turbines was also investigated, and partially linked to insect migration.[43] In 2016, it was demonstrated that several bats

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were eating diurnal insects resting on wind turbine towers, meaning that aerial-hawking species are able to switch to gleaning when flightless prey is available. In another study, bats were observed foraging at turbines during migration over the Baltic Sea waters and islands, indicating a risk of collision also with offshore wind farms.[73]

Habitat Loss. The issue of habitat loss is not common among studies conducted in the Baltic Sea region. One study focused on a single species, *Barbastella barbastellus*, and determined that wind turbines are not directly threatening this species because of a very low collision risk.[74] However, the importance of mature deciduous woodlands and spruce forests for the species is noted, meaning that wind farms can still have an impact through poor planning, siting, and building which leads to the destruction of these habitats as stated in the previous section.[74]

Disturbance. The issue of the avoidance effect caused by wind turbines on bats has not been studied in the Baltic area so far.

3. AVOIDANCE AND MITIGATION

3.1. Methods and Tools Used in Europe. Many methods have been developed to avoid or reduce the impacts of wind turbines on bats, but only a few proved to be efficient.[15,16] The objective of this review is not to introduce all these approaches, but to focus on the ones currently used in Europe on operating turbines that have shown to be effective. Some of the methods presented decrease the collision risk and therefore the fatality rate of the wind farm, others attempt to avoid destruction of important habitats and features for bats. As soon as a site needs to be chosen for the establishment of the turbines, methods to ensure low or zero impact on bats in the wind farm project can be considered and used well ahead of time; preplanning is also the best way to reduce the costs of mitigation measures.

Indeed, the first and probably the most effective way to avoid impacts is the choice of the wind farm site itself, a crucial step which cannot be taken lightly, as there are multiple factors to consider just regarding bats. General guidelines recommend avoiding areas which are extensively used by the involved taxa or which play an important role in their life cycle, principles that can also be utilized for birds and other taxa. For bats, this means avoiding, for example, hedgerows, forest edges, and other wooded linear features, as they are extensively used for commuting and foraging.[33,44,50,75−79] Wetlands are also important sites for foraging.[44,75] Summer and winter roosts can be in various location types, but caves, forests and old trees, ridges and cliffs can be highlighted.[31,80,81] Bat colonies are sometimes known and monitored, therefore studying local or national bibliography can reveal these data.[31] Migration flyways are often located on the coast or in fluviatile valleys along rivers.[32,82] Another recommendation is to avoid natural reserves, national parks or any protected areas, as they are designed to protect important sites for numerous endangered or vulnerable species, including bats.[15] These zones usually have defined limits and specific regulations, often forbidding the construction of wind turbines inside their perimeter anyway.[83] Buffer zones around these sensitive areas are advised.[84,85]

A similar approach to avoiding sensitive areas can also be adopted for micrositing, i.e., the positioning of turbines and other facilities—roads, power lines, and substations—within the wind farm area. EUROBATS[31] recommends a minimum distance of 200 m between wind turbines and wooded features such as forests and hedgerows, a distance rarely respected, and that also proved to be insufficient to avoid the disturbance of bats.[25] Studying flight corridors on-site is essential to understand their importance for migratory and commuting bats, and to choose the position of wind turbines accordingly: keeping a distance from the flyways and placing turbines parallel to them.[83,86] A simple wind farm design, such as turbine rows or clusters has been found to be effective in keeping the impact on habitats low.[5] The adequate distance between each tower is difficult to assess as both tight and wide spacing have pros and cons: turbines closer to each other can reduce the cumulative avoidance effect of turbines[25] and footprint on habitats,[83] but also decreases the commuting possibility between each turbine, because of the aforementioned avoidance effect, while a longer distance would result in the opposite.

Turbine characteristics can also be a way of reducing collisions with bats, as it seems that turbine height and blade size influence fatality rates: a positive correlation has been reported between rotor diameter and fatalities.[12,87] The overall number of turbines in a farm has no influence on the fatality rate of each single turbine in it, and neither has lighting on turbines.[11,12,31,88] Still, any nonmandatory lighting should be avoided as recent studies demonstrated it can still attract migratory bats.[89,90]

As impacts and their mitigation during the construction step are not specific to wind farms, but can occur at any construction site, they are not extensively dealt with here. The foremost recommendations are to pay attention to habitat degradation by limiting excessive spreading of human activity with fences and cordons,[91] and to work during periods when bat activity is low, but not during their hibernation period.[31] Restoration of the site after dismantling the turbines is necessary and will benefit all fauna species, including bats, especially on sites extensively modified during the construction of the farm.[92,93]

Curtailment of wind turbines during their operating time is used when siting or modification of turbine characteristics are not enough to avoid all impacts. This is usually the case with fatalities, which are difficult to elude because the possibility of bat presence, and therefore collision risk, always exists. There are two possible ways to set up curtailment: the first method is to use models based on local environmental parameters and bat activity to predict and stop turbines during high-risk periods of collision, a method that has proven to be efficient on multiple occasions.[35,94,95] The second method is to use cameras and acoustic detectors to spot the presence of bats close to wind turbines and stop the rotor when a certain activity threshold is reached.[96−99] Both these approaches are widely used in Europe through different models and technologies, each presenting benefits as well as inconveniences.

Contrary to North America, where wind speed is the sole parameter used to curtail turbines,[100,101] in Europe other factors known to influence bat activity are considered, such as time, season, temperature, rain, and fog (Figure 2).[12,26,34] Because of this strong correlation, these factors can be used to define periods where bat collision risk is high and to shut down wind turbines during these periods.[35,95,100] Several studies have shown that the economic cost of this measure is small, as low wind speed periods when bats are the most active are also periods of low energy production. Even less profit is lost when

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the curtailment algorithm is based on site- and species-specific data.[31,34,35,95,100] To retrieve these data, weather and bat activity at rotor height have to be monitored for at least one year after the initiation of turbine operation. Using bat activity data from ground height is not recommended as its correlation with bat activity at rotor height is weak.[102] However, activity data from a wind farm nearby can be used if conditions such as surrounding habitats or turbine size, are similar.[102] It is also possible to use weather masts or equivalent to set acoustic detectors and monitor bat activity at rotor height before turbine construction.[102,103] Despite this, the more relevant data are collected directly at rotor height with the turbines already in position. During the first operational year it is possible to use a nonspecific model for curtailment while site-specific data are not available, as has been conducted in Germany.[95]

Beginning in the second year of operation, monitoring data from the previous year can be utilized, and the process can be repeated with each year of activity monitoring at the farm used to improve results.[95]

Used separately or in conjunction with multivariable models, detection of one or several bats close to the turbine is also employed in Europe to trigger shutdown. The principle is simple and effective, but the existence of false negative and positive results reduces the efficiency of such a method in practice: detectors can spot an approaching bat when there is none (false positive), but also miss a bat flying close by (false negative), due to the small size of an average bat in the region.[16,97] However, as the problem is purely a question of technology, it is only a matter of time before more effective detectors are developed and utilized. There is also a lack of external studies providing performance assessment of such technologies.[97]

Other approaches such as deterrents have been proposed, sometimes tested but never extensively used to reduce fatality numbers in Europe or elsewhere.[104] Habitat management can be used to reduce attraction factors for insects at wind turbines by keeping the vegetation and water levels low.[31] Management can also be employed to compensate for habitat loss by preserving, restoring or creating new roosts (natural or artificial), commuting and foraging habitats such as hedgerows, wetlands, or woodlands.[61,81] However, measures are usually species-specific and can be difficult to put together when considering other taxa simultaneously.[16,105] Finally, the efficiency of these offsetting measures has rarely been investigated in Europe.[60,106] Therefore, avoidance and reduction methods must be preferred for bat mitigation, with appropriate siting and curtailment as the favored measures.[31]

3.2. Methods and Tools Used in the Baltic Sea Region. There is currently no published study in peer-reviewed journals focusing on mitigation methods used for wind farms in the Baltic Sea region, despite the probable use of several methods. Information from other sources, such as EUROBATS or national wind power associations, is still rather scarce.

In Estonia, and despite consideration of bats in wind power projects, there is no national guideline on mitigation for bats. Use of mitigation techniques, such as blade feathering or increased cut-in speed, has not been reported.[66] The situation is similar for Finland[63] and Latvia.[69] Lithuania is the only country in this study where the use of increased cut-in speed and deterrent is confirmed, but additional information on their use is unavailable.[67] In Finland, macro- and micrositing are common practices, with the avoidance of nature reserves as an example. However, decisions are rarely based only on the presence of bats in the vicinity of the wind farm. In addition, there is no guideline to help developers with siting in the country. Similar recommendations have been proposed for Sweden, but there is no information on their realization in practice.[29] However, in Sweden, mitigation methods such as curtailment have been reported for birds but not for bats.[19] The same report describes stopping rotors during high-risk periods as a viable solution to mitigate bat fatalities in Sweden but it is unclear whether it is actually in use.[19] We do not have any information for Russia, where the use of wind power is still emerging.

4. TOPICS IN NEED OF ATTENTION

Despite clear improvements in bat research in Europe and worldwide, there are still several issues that need to be investigated. Examples of these are the lack of knowledge on a certain aspect of bat biology, such as migration, or flaws in current materials and methods used to study the impacts of wind farms on bats. It also can be dependent on the geographical location within Europe, with a need for impact estimation in the countries of the Baltic Sea region for example. Below we present some topics summarized under bat ecology, impacts of wind farms, bat surveys, curtailment, and framework, that should be addressed to better understand and resolve the issue of the impacts of wind power on bats, in the Baltic Sea region specifically, but without ruling out possible options for the whole of Europe.

4.1. Bat Ecology. *Knowing Your Bats: Distribution, Roosting, Commuting, Foraging, Diet Preferences.* The European boreal region shows specificities in terms of climate, habitat, or seasonality that affect bats living there in multiple ways. For example, some species migrate to Central Europe during the autumn to avoid the harsh winters of the boreal region. Individuals travel thousands of kilometers twice a year, also crossing the open waters of the Baltic Sea at several points and using the coastline for orientation.[65,73,107] Only a small fraction of this behavior has been studied so far, and there is a considerable amount of information that we do not know yet about this taxon, even outside the current subject area of wind farm impacts. Therefore, gathering data on the foraging habits,[23,76,108] diet preferences,[77−79,109] roost selection,[110] and distribution ranges[22] of bat species inhabiting the countries surrounding the Baltic Sea should be a primary focus. Obtaining these data would only be a first, but vital step in understanding the impacts of wind farms in the region and ensure efficient avoidance and mitigation measures. For example, it would allow for the creation of sensitivity maps based on bat preferences for roosting and foraging, maps that could be employed for a better siting of farms. Other data on diet or mating habits could be applied to mitigation measures, to reduce the attractiveness of wind farms to insects and bats.[43,46]

Special attention should be given to the eight species defined as high-risk regarding collision with wind turbines,[19] but this does not mean disregarding other species, as they can be impacted in different ways.[25] For instance, there is concern for *Eptesicus nilssonii*, as it is probably the most common bat in the Baltic Sea region and furthermore, an aerial hawker foraging in the open, sometimes at a considerable height.[19,64,65]

Migratory Bats and Flyways. Migratory bats and their flyways are an additional topic where more data are severely needed, not only for the Baltic Sea region but on the continental scale. The most important questions are to localize the main and secondary flyways, as well as the concerned species.

In northeastern Europe, the main migratory species is the high-risk species *Pipistrellus nathusii*, as it migrates from and through all the countries surrounding the Baltic Sea during its autumn migration (Figure 1).[65,111] These movements could lead to increased risk of collision at certain locations, such as the western coast of Finland, where the use of wind power is increasing.[65,112] The same applies to *Pipistrellus pygmaeus*, which is more present in Sweden and the Baltic States. This species has been identified as a long-distance migratory species too, but more data are needed to understand the behavior better.[113] Identification of its flyways and summer roosts is essential to set up a conservation strategy for this species in relevant areas. *P. pygmaeus* is facing a high risk of collision because of its open-space foraging behavior, therefore fatality rates must also be monitored.[19]

Bats in Woodlands. While deciduous forests are often considered to be one of the most important habitats for bats,[114,115] several studies have shown that coniferous forests can also host rich and abundant bat communities.[116,117] In both case, bats prefer the oldest patches of woodland.[23,76,116,117] Given that the majority of the woodlands in the European boreal region are coniferous, they are the most important habitats for bats in this region.[23,76,114,115]

Because of the large forest cover in the European boreal region, wind farms have already been built in these habitats and their numbers will most likely increase in the future.[19] Therefore, the potential impacts of wind power in boreal forests must be assessed, by investigating its effects on bat activity at ground height in forests and at their edges, above the canopy and at rotor height, taking into account the distance between canopy and rotor radius.[118] Research should pay special attention to species foraging at medium heights, such as *Eptesicus nilssonii*, as they might face greater risk of collision than high-flying species when turbines are located in forests.[119] Activity of low- and medium-height flying species is dependent on the proximity to woodland, unlike high-flying species.[119] Evidence already exists that *Eptesicus nilssonii* spends a significant amount of time at a height in southern Finland,[64] which puts this species at collision risk.[37] More surveys on activity at canopy and rotor height are required for the boreal region.

4.2. Impacts of Wind Farms. *Attraction Effect.* Identifying why bats are attracted by wind turbines would greatly advance the design of effective mitigation measures for this effect. A reduced or removed attraction effect would decrease collision risk and fatalities without the need of further measures such as curtailment or deterrence.

However, given that the underlying reasons for bat presence vary from one site to another, such identification could be required for each wind farm, or even each wind turbine. Furthermore, attraction factors cannot be assessed before the construction of the wind farm. We propose setting up measures in advance to reduce the influence of the main factors: prey presence, roosting, mating, and meeting possibilities.

While answers to some of these problems already exist, there are no practical solutions available. For example, the presence of prey insects in the vicinity of turbines can be reduced by making the turbines less attractive for insects. This could be achieved by changing the turbine's color to reduce infrared and ultraviolet reflectance.[45] However, this method requires painting the turbines purple for maximal efficiency, which is not very compatible with the objective of blending the turbines into the landscape. In the same study, the authors also argue that the heat-absorbing properties of the colors and material must be considered as they also influence insect attraction, but other, yet unknown parameters could be at play too.[45]

Reducing the possibility of roosting at wind turbines is easier, as one only needs to avoid any openings on the outer structure, simply by removing them or by covering them with mesh. However, as bats seem to confuse turbines with giant trees, they are likely to explore them closely expecting to find a roost, even if one does not exist. Therefore, reducing roosting possibilities does not necessarily reduce either the attraction effect or the risk of collision.

In summary, there are currently no practical solutions available to make wind turbines less attractive for bats or for insects. Therefore, the attraction effects on bats and insects still need to be studied further in order to develop practical and cost-effective solutions.

Avoidance Effect. As observed in France, all species of bats can be affected by the presence of wind turbines within their home range, even if they are not directly threatened by collision risk.[25] This is why research should simultaneously study direct fatality events for high-risk species without neglecting "low-risk species" such as *Myotis* spp. or *Rhinolophus* spp. species. These species rarely encounter mortality at wind turbines, but are most likely impacted through habitat loss as a consequence of site construction.[25] The avoidance effect observed in France affected all the species, with decreasing activity within a radius of up to 1000 m around each turbine.[25] The avoidance effect should be considered in the boreal biogeographic region and whether species are affected on a similar scale.

Turbine Characteristics. Turbine height and rotor diameter have been investigated as potential factors influencing bat fatality rate, showing a positive correlation between the latter and each of the turbine parameters: the larger and higher they are, the higher the mortality.[12,120] However, the current trend is to produce larger turbines, as it improves energy production and reduces CO_2 emission.[121,122]

Moreover, newer turbines tend to be able to produce energy at lower wind speed, when bat activity is at its highest.[123] This is also an issue for curtailment implementation as cut-in wind speed is usually the first parameter to be changed in order to reduce bat fatality rates. This change will increase the production loss of curtailed turbines, which might raise resistance from wind power companies. However, it is not known whether loss of income related to curtailment can be partially or entirely compensated by the improved production of newer larger turbines. Moreover, the average wind speed has increased since 2010, thus boosting production of wind turbines.[124]

4.3. Bat Surveys. *Preconstruction Surveys in Europe.* The quality and usefulness of current bat surveys done during an environmental impact assessment (EIA) or similar procedure for wind farm projects are also a source of concern. Researchers and authorities recommend extensive surveys over a long period for a better estimation of bat presence at a given site.[19,125,126] However, current assessments are failing to correctly estimate future bat presence and activity once the wind farm is built.[127] This is probably due to the attraction effect of wind turbines on bats, which cannot be measured

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prior to construction, and the change in habitat and landscape caused by the construction of the turbines, which can also have an effect on bat activity. Another reason for inadequate assessments is the high variability of bat activity in space and time, which would require numerous sampling sites over several years to obtain a usable estimate of this activity.[125,128] However, this comes at a greater cost, it slows project progress, and is ultimately difficult to execute.[125]

The main consequence of incorrect predictions of bat activity and collision risk at future wind turbines is the implementation of inadequate or incorrect measures to mitigate impacts.[127]

To obtain a better estimation of collision risk, surveys at rotor height using weather masts or similar structures have been recommended by EUROBATS.[31] The relationship between bat activity at rotor height and collision risk was investigated and showed a strong correlation between the two, independently of bat density.[103] The longer a species spends at rotor height, the higher its collision risk.[103] Thus, there is a strong interest in using these masts to survey bat activity at future wind farm sites.

However, it is not clear if bat activity observed at weather masts is comparable to the activity later observed at wind turbines. It is likely, that due to the obvious physical differences between the two structures, they may not fulfill the same "role" with regards to bats, insects, and the attraction effect on both taxa. Wind turbines are clearly larger and can store more heat, which is an attraction factor for insects and therefore of bats.[19] Roosting possibilities are also very reduced on weather masts, especially when they are lattice towers. Nonetheless, as bats are known to be attracted to the tallest structures in the landscape, weather masts and wind turbines can both act as meeting and mating sites for bats.[129]

However, similarities between activity at these two types of structures has only been investigated in North America with migratory tree species.[129] There is a clear need to conduct a similar study in Europe to determine if this is also the case for European high risk species. Establishing the correct relation between activity at weather masts and activity at wind turbines could then allow a quantitative prediction of collision rates. Several models have been developed for German wind farms and have this potential of prediction but are currently only used for curtailment purposes.[95,130] They could allow extrapolation of bat activity at future wind farms, based on observed activity at a tall structure on the site.

Moreover, the recent discovery of avoidance effect impacting all species[25] should be recognized as a call for better consideration of these "low-risk" species during the preconstruction surveys, especially for species with an unfavorable conservation status, at least until this phenomenon has been investigated further.

Surveys in the Baltic Sea Region. The situation in the Baltic Sea region is different regarding ecological impact assessment, as the base surveys are usually lighter. In Finland for example, active monitoring at ground height is the common method, while monitoring at rotor height is seldom used. In contrast, bat surveys during the EIA step in France require searches for roosts in the already existing data and on the site, and acoustic monitoring at rotor and ground height to be conducted during the entire active period of bats (usually March to November) at multiple sampling points for an exhaustive data on the use of the site by bats during the whole year.[131] The reason for the very light surveys in Finland could be that wind farms are usually built in managed forests where bat density and roosting possibilities are low most of the time.[76] It could also be that the impacts of wind farms on bats are supposedly very low in the country because of a low density and a limited distribution of species. However, the actual impacts have never been investigated, and the distribution and population density of species in the country are poorly known.

Therefore, it is evident that improved guidelines are needed for bat surveys for wind farm projects in the Baltic Sea region. However, the questions remain of whether the guidelines should be based on the model preferred in Central Europe, which fails at assessing and preventing future impacts, or, whether money and time should be reserved to consider new methods to correctly assess impacts of wind farms on bats in the Baltic Sea region.

None of the six countries we focused our work on in this study had adequate estimations of how many bats are killed annually at wind farms. For example, postconstruction monitoring is very rare, if nonexistent in Finland.[62,132,133] Sweden faces a similar problem as none of the monitoring programmes in the country have been adequately executed, and therefore fatality rate cannot be estimated.[19] Therefore, putting postconstruction fatality and activity monitoring in place for all current and future wind farms would be a suitable starting point. It would allow collecting actual data on bat fatalities in the six countries of the Baltic Sea region, and at the same time would reveal the potential impact of each farm with the possibility of mitigating them. Implementing this approach is not easy and free of cost as carcass searches are quite time-consuming, and the recommended protocols are not necessarily adapted for countries in the boreal region.[19,62] Executing these protocols correctly also requires qualified professionals to perform the carcass searches and data analysis for all the wind farms.[28] Furthermore, the cooperation of wind power companies, developers, and farm managers is essential. Governments and public authorities must act as an incentive for implementation of this monitoring, with the use of laws and controlling bodies as a last resort.

There is no more information available on pre- and postconstruction bat surveys in the other four countries.

As in Central Europe, monitoring bat activity and mortality postconstruction should be conducted for at least two or three consecutive years in order to reduce the influence of annual variability of bat activity, and during their whole active period from spring to autumn.[35,95]

Surveys in Woodlands. The development of wind power in forests also raises the question of bat surveys during impact assessment and how they are conducted. Establishing wind farms in such habitats requires careful planning with regards to the choice of a site and thorough site-specific bat surveys.[31] Impact assessments for wind farm construction in coniferous woodlands is challenging as tree felling for turbine pads and roads has significant impacts on the habitat.[31] This kind of change clearly affects bat presence and activity, even in coniferous forests, but cannot be assessed before the actual construction of turbines.[134,135] There is a need to improve or change the way surveys are conducted and this is even more important for this peculiar type of landscape that endures a great deal of change with the construction of wind turbines. Moreover, postconstruction monitoring and carcass search protocols must be investigated as they do not necessarily fit the conditions found in woodlands, even less the ones from the boreal region because of the often dense vegetation at ground level.[62] Similar thought must be given to EUROBATS recommendations of minimum distances between wooded features and wind turbines as they are not really compatible with the important tree cover of the boreal biogeographic region: they have already been neglected and will be difficult to comply with in the future.[31] The situation is similar in other parts of Europe where the 200 m minimum distance is not complied with.[25]

How to Correctly Assess Impacts of Wind Farms on Bats? The methodology for impact assessment for bats is flawed at present, and it should be redesigned to better fit its purposes. Some argue that postconstruction monitoring should be given more importance in order to assess the actual impacts of a wind farm.[19,127] Preconstruction investigations and surveys could still produce data on species presence and activity levels at the site, which could help determine the feasibility of the project regarding impacts and mitigation costs.[19,127] Preconstruction surveys would only assess potential impacts while postconstruction would assess the real impacts.[18] A similar process can be seen in Portugal and France for example, where postconstruction activity and mortality monitoring are mandatory for all wind farms, and therefore allow the assessment of the actual impacts of the farm, with the possibility to implement mitigation measures such as curtailment if impacts are higher than expected.[67]

We recommend efforts to be concentrated on adequate and reliable postconstruction monitoring to assess the real impacts of all wind farms in Europe. To conduct this monitoring, EUROBATS guidelines should be followed and enforced in most of the countries, but for others such as the Baltic Sea region countries, the guidelines must be adapted when local conditions prevent reliable surveys from being conducted.

Recent fatality estimators such as Genest could also help, thanks to their incorporation of varying searcher efficiency, search areas or vegetation cover.[136] Therefore, conditions in the Baltic Sea region that make the implementation of EUROBATS guidelines unsuitable, could be taken into account during a fatality estimation.

4.4. Curtailment. The curtailment of wind turbines appears to be an adequate solution to reduce bat fatality, showing significant decreases in annual rates at multiple sites.[35,95,137] In Germany for example, shutdown algorithms are being increasingly used and are now recommended by authorities;[138] they are used in conjunction with a defined absolute threshold for annual bat fatality (one or two bats killed per turbine each year, depending on the region).[95]

This method has several clear limitations. The first one being that it does not completely prevent fatalities of endangered species, which are also protected at European and national levels.[123] Moreover, there is a total absence of consideration for any cumulative impacts generated by curtailment on a greater scale.[94,137] Indeed, while having a fixed value for the number of bats killed per turbine, it omits consideration of the global fatality rate which increases each time a new turbine is built and operated with this algorithm.[94,137] It also does not consider additional mortality from other sources besides wind turbines and the pressure placed on bat populations by all these threats; populations which will probably not be able to sustain such pressure in the long term.[137,139,140] Despite supposed (negative) trends for bat populations, there are no precise or reliable figures concerning their demography or the impacts of wind power on them.[137,139] Because of this, defining an absolute value for mitigation is risky, and defining an appropriate value is impossible.[94,139] Curtailment can be effective in reducing bat mortality at one site but it does not mean it is efficient enough to prevent population collapse on a larger scale.[139] With species not limited by region or state boundaries, and with some of them flying thousands of kilometres during migration, fatality rates cannot be decided separately for each wind turbine, but need to be considered and designed on the continental scale.[94]

However, it is extremely difficult to design an alternative solution without flaws. One possibility would be the use of several mitigation measures in parallel.[97] First, curtailment based on environmental factors and bat activity at rotor height at the site is still the most efficient way to reduce mortality while limiting the cost for wind power companies. Combined with this, cameras or microphones to detect any approaching bat can be employed to either shut down the wind turbines for a limited time or trigger deterrents. However, efficient deterrents for bats at wind turbines are yet to be tested.[16] Another recommended solution is to increase cut-in speed until a threshold where bats cease to fly or encounter mortality at wind turbines. This is a very effective solution from a conservation and legal point of view, but one that generates additional revenue losses.[123]

An ideal mitigation strategy would require data on European bat population numbers and trends that would allow the quantification of the share wind power can remove on bat populations in each region in a way that reaches conservation and wind power objectives, similar to game management.[94] Unfortunately such data will not be available for quite some time.[123,137,139] This method also means that protected bat species would still be killed at wind power sites.

4.5. Framework. Besides research on bats and on the impacts of wind farms, there is a clear necessity to improve the framework surrounding the research itself. One measure to improve the efficiency of research is to increase the availability of the results to a greater audience, including researchers, wind power companies, public authorities, and policy makers. This needs to be conducted at multiple levels, with the national and continental being the most important, but with adequate weight at local levels too.

International communication and collaboration is of the highest importance when considering an issue that knows no borders: throughout Europe bats of the same species, sometimes belonging to the same population, are killed or are being disturbed by the same anthropogenic structures. As our current knowledge on bats in Europe is far from complete, effective sharing of available data is necessary: both scientific research on bat biology or ecology, and also the results of pre- or postconstruction surveys, should be made available to stakeholders, the raw data included. The objective of such sharing is simple: the more data available, the more efficient and suitable the impact assessment, avoidance, and mitigation plans.[126,141] A good example of this is the Bat Acoustic Monitoring Visualization Tool in North America.[142] However, even easily accessible data can be difficult to exploit, as protocols and materials employed to obtain them often differ from one study to another. This is why methods should be standardized for Europe, by using the recommendations made by EUROBATS on postconstruction monitoring, for example.[28,31] Furthermore, these recommendations and guidelines should be given more legal weight by the European Union or

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the states belonging to it. However, some space should be left for adaptation in certain conditions, as the current recommended protocols do not work everywhere.[62]

There is a lot of room for improvement in the Baltic Sea region specifically, but one of the most essential aims should be the improvement of communication and cooperation, both at national levels and between the countries, and between all of the stakeholders: wind power companies and associations, authorities and governments, associations, environmental consulting companies, and of course researchers. Northeastern Europe is a key area for several bat species that breed there during summer before migrating southwest for overwintering. All the countries in the region also have a great potential to utilize wind power, with the generation capacity growing over the last years, and it is expected to keep increasing in the future. Therefore, the countries in this region have an important role to play in bat conservation and prevention of the impacts of wind power.

Our experience during the writing of this review is what has led us to emphasize the importance of communication. The collection of data on wind farms and bats conducted to produce this review has been a struggle and required much effort because of the absence of communication between all the stakeholders. It forced us to have to individually ask every party involved for any information and reports they had, as no organization is collecting and archiving these. It was also a good opportunity to notice that the parties involved are not aware themselves of what is taking place in their country or have knowledge on who are the people responsible for this subject.

5. CONCLUSION

The impacts of wind power on bats in Europe is a unique issue that requires more collaboration and standardization of research within the countries to resolve the problem because it affects the same species and sometimes the same populations across the continent. At the same time, Europe offers a great diversity of climate, biome, and habitats influencing species in a plethora of ways, resulting in significant differences in individuals of the same species whether they are located in Southwestern or Northeastern Europe. These differences need to be studied to obtain a better understanding of the various species or phenomena.

Unfortunately, the issue of the impacts of wind power on bats is still not entirely acknowledged in some countries, such as Estonia, Finland, Latvia, Lithuania, Russia, or Sweden. Data on bat biology and ecology are lacking and they are necessary if a comprehensive knowledge base is to be created with respect to the impacts of wind turbines and in order to solve the issue. A legal framework has also been delayed on the subject, most likely because of the missing data. All these requirements have to be addressed quickly because of the constant rise in the construction of wind farms in these countries, and above all, because of the important role Northeastern Europe has for bats.

While some specific topics in this large issue, such as environmental impact assessment or curtailment, are called into question, the challenge in Europe is to improve research and cooperation within every country and between them, on an issue that takes place on a very diverse continent.

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Notes

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