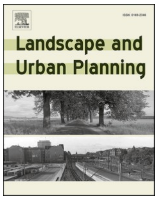
Landscape and Urban Planning 231 (2023) 104636

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan



Research Paper

The presence of wind turbines repels bats in boreal forests

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HIGHLIGHTS

- Presence of *Eptesicus nilssonii* and *Myotis* spp. are higher further from wind turbines located in forests.
- The avoidance of wind turbines or their surroundings could mean important loss of habitats for bats.
- Bat activity at wind power sites in forests varies with night length and season in the boreal zone.
- Mitigating this avoidance effect in current and future wind farms requires stronger regulations in Finland and the rest of Europe.

ARTICLE INFO

Keywords:
Wind turbine
Bats
Avoidance effect
European boreal region
Wind power planning

ABSTRACT

Impacts of wind power on bats are usually evidenced by the recorded fatalities, while other impacts are not well understood or considered during project planning. However, wind turbines may affect use of the surrounding habitats by bats. Little is known about such impact, especially in the European boreal biogeographical region. We studied the consequences of operating wind turbines on the presence and activity of bats in forests. We simultaneously monitored bat acoustic activity at 84 sampling sites placed at 200 m intervals from 0 to 1.000 m (2 recorders per distance class), over four months and at seven Finnish wind farms located in forested habitats. Our results show higher presence and activity at 600 m and further from turbines for *Eptesicus nilssonii*, and higher presence at 800 m and further for *Myotis* spp. We also saw an increase in bat activity during midsummer, which may be due to increased use of forest canopy cover during the short nights at this time. These results indicate a potential loss in habitat quality around wind turbines, e.g., a greater number of open areas in forests unfavourable to certain bat species. This lower activity and presence could also be an indication for active avoidance of the wind turbines from the bats. Furthermore, these results are the first of their kind for *Eptesicus nilssonii*, and for the European boreal biogeographical region. They show undeniable impacts of wind power on bats in Finland, and enforce the requirement for better consideration of bats during the development of such projects in Finland. Similarly, these results show impacts of operating turbines on habitat use by bats, impacts that now must be considered in Europe. We also call for investigation on the causative mechanisms of the observed effect, to better facilitate mitigation.

1. Introduction

Wind power is playing a substantial role in the transition to clean energy production in many countries (Ember, 2021). Being a renewable source, the exploitation of wind does not generate pollution (Edenhofer et al., 2012). Unfortunately, developing and operating wind farms can still have negative impacts on landscape, human health, environment or biodiversity, and thereby lead to lower social acceptance of wind turbines or damages to fauna and flora (Buchmayr et al., 2022; Dai et al., 2015; Saidur et al., 2011).

The impact of wind power on bats have been known for decades. Fatalities were first reported in 1972 and have since been intensively studied. Affected species, seasonal peaks and the influence of weather conditions on bat fatalities have been largely described, at least for Europe and North America (Hein & Schirmacher, 2016; Rydell et al., 2010a). Bats are also affected by habitat destruction during the construction of wind farms, with the potential loss of important features for roosting, commuting, or foraging, such as wetlands or hedgerows (Gaultier et al., 2020; Reusch et al., 2022). Knowing all the characteristics of these impacts have since led national and international

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https://doi.org/10.1016/j.landurbplan.2022.104636
Received 3 June 2022; Received in revised form 3 October 2022; Accepted 8 November 2022

organisations to propose guidelines and measures on how to correctly plan wind power projects in order to avoid or minimise impacts on bats (Rodrigues et al., 2015). Such mitigation measures include avoiding construction close to known bat roosts or other important features and installing curtailment on wind turbines to decrease the risk of fatalities, or designing wind farms with an intent to reduce their footprint on habitats (Gartman et al., 2016a, 2016b). These measures are far from being completely respected by wind power developers, even in developed countries (Barré et al., 2018; Voigt et al., 2022). Most of all, these measures are not always enough to mitigate impacts of wind farms on bats, because the mortality is still taking place and very difficult to offset (Hayes et al., 2019; Rodrigues et al., 2015; Voigt et al., 2015), especially when cumulative impacts of several wind farms are considered at a larger, landscape scale (Roscioni et al., 2013).

While possible causes of fatalities have been investigated (Cryan & Barclay, 2009; Guest et al., 2022; de Jong et al., 2021), the phenomenon known as the avoidance effect appears seldom in peer-reviewed literature. Most of the research on this topic has been conducted in Western Europe, on both small and industrial-sized turbines (Barré et al., 2018; Ellerbrok et al., 2022; Leroux et al., 2022; Millon et al., 2015; Minderman et al., 2012, 2017; Reusch et al., 2022; Richardson et al., 2021; Roeleke et al., 2016). A similar effect has also been observed in the Pacific islands (Millon et al., 2018). Most of these studies show that bat acoustic activity close to wind turbines is lower than further away from the turbines, indicating that habitat around turbines appears less attractive or are even avoided, or that wind turbines are directly avoided. By doing so, presumably suitable habitat around the turbine is effectively lost to bats (Reusch et al., 2022). Moreover, all species, regardless of their sensitivity to wind power related mortality, can be affected by the avoidance effect. While collisions mostly impact migrating, open space or edge space foragers such as *Pipistrellus nathusii* or *Nyctalus noctula*, species considered as narrow space foragers, such as bats in the genuses *Myotis or Plecotus*, have shown to be also affected by the avoidance effect (Barré et al., 2018). Moreover, the reasons for avoidance are currently unknown, although e.g., distance to hedgerows could play a role (Leroux et al., 2022), while turbine lighting and noise emission have also been proposed as possible causes (Barré et al., 2018; Leroux et al., 2022). However, literature on this topic is still scarce, and sometimes contradictory (Richardson et al., 2021; Leroux et al., 2022), meaning the phenomenon is not fully understood and deserves more attention. A better comprehension is required if efficient efforts to avoid or mitigate the problem are to be made.

While most data have been collected in agricultural landscapes of Western Europe (France, United Kingdom, Germany), the avoidance effect has so far not been studied in other landscapes or regions of Europe. In particular, there is no data for the woodland-dominated European boreal biogeographic region (Sundseth, 2009). Moreover, the impacts of wind power on bats in this part of Europe have not been studied in detail, even though especially the coastal areas of the Baltic Sea are considered to be of great importance to bats (Gaultier et al., 2020; Ijäs et al., 2017). This is particularly true for Finland, where there is almost no literature on impacts of wind power on bats (Aminoff, 2014; Blomberg, 2016; Ijäs et al., 2017), despite an important development of wind power in the country currently (Wind Power in Finland, 2022). Therefore, obtaining any data on impacts of wind power on bats in this part of Europe is of great relevance right now, and could favour the conservation of bats in the countries there.

Here, to understand whether and how bats respond to the presence of wind turbines in the boreal forests, we studied bat acoustic activity of the most common species (*Eptesicus nilssonii*) and species group (*Myotis spp.*) in Finland, at a landscape scale, up to 1,000 m from operating turbines. The study made use of passive recorders to sample bat activity at 84 locations simultaneously, at seven wind farms located in woodlands on the western coastline of Finland. Acoustic sampling took place every night for almost four months, allowing us to collect a large dataset. This landscape and region were chosen because of the tendency for Finnish wind farms to be built there at the moment (Asko Ijäs, personal communication, March 30, 2022). We hypothesised that bat presence and activity would correlate positively with increasing distance from wind turbines for observed taxa. Finally, in view of our findings and other recent research, we expressed the need for stronger regulations and their enforcement regarding the loss of habitats for bats due to wind power in Finland (Blomberg, 2016; Gaultier et al., 2020; Ijäs et al., 2017) or in Europe (Barré et al., 2018; Leroux et al., 2022).

2. Materials & methods

2.1. Study sites

Data were collected at seven wind farms located on the western coast of Finland, in the regions of Ostrobothnia, Satakunta and South Ostrobothnia (Fig. 1) All wind farms consisted of 5 to 34 wind turbines (mean = 15) with a mean height of 206 m at the highest tip of the pale (standard deviation = 4.4 m), and a mean rotor diameter of 136 m (standard deviation = 11.2 m). The distance from the wind farms to the coastline was between 2 and 18 km, with an average distance of 10 km (standard deviation = 6.2 km).

We decided to include canopy cover in our analysis, using three classes: [x > 95 %], [95 %>x > 50 %] and [x < 50 %] where x is the percentage of area covered by tree canopy, regardless of their species, in a 150-m radius around the sampling point. In our study area, forest patches were of a similar age (mean = 49.33 years old, standard deviation = 12.32) and similar composition (deciduous tree cover mean = 9.95 %, standard deviation = 7.85 %), which is representative of the forests of Finland and the rest of the boreal region (Luke, 2017), therefore we did not include these two parameters in our analysis.

2.2. Sampling design

We studied bat activity along forest edges or forest roads, with a distance gradient of 0 to 1,000 m from the nearest wind turbine. These features are important to bats as commuting routes, and a higher number of bat species are likely to be found using these habitats for foraging with both close-space and open space habitats present (Vasko et al., 2020). Moreover, wind farm construction contributes to the creation of some of these open areas in forests when roads and pads are cleared for the turbines.

We sampled six distances (0, 200, 400, 600, 800 and 1,000 m) to the nearest turbine in duplicate at each wind farm (Fig. 2), adding up to 12 sampling points for each wind farm, and adding up to 84 points in total. We recorded bat acoustic calls at all 84 points every night, starting June 1st, 2020 and ending between September 10th and 20th, 2020, depending on the recorder (16 weeks).

Sampling commenced 30 min after sunset and was concluded 30 min before sunrise, with 5 min recording periods alternating with 10 min of sleep. The length of night varies considerably in Northern Europe, shifting from lasting twilight in June (mean = 5.42 h) to full nights towards the end of our sampling period (mean = 11 h) in September. We used AudioMoth recorders (Open Acoustic Devices, version 1.1) at every sampling point. Each recorder was strapped on to a tree along an edge, at around 2 m from the ground, with the microphone facing an open area (road, path or clearing).

2.3. Bat call analysis

We used Kaleidoscope (Wildlife Acoustics) for automated identification of bat calls, before proceeding to manual verification of the identifications. Signal detection parameters were the following: frequency range between 8 and 120 kHz, detected pulse length between 2 and 500 ms, with a minimum number of pulses of 2 and a call sequence maximum length of 5 s.

A sample of *E. nilssonii* calls was manually checked to assert the

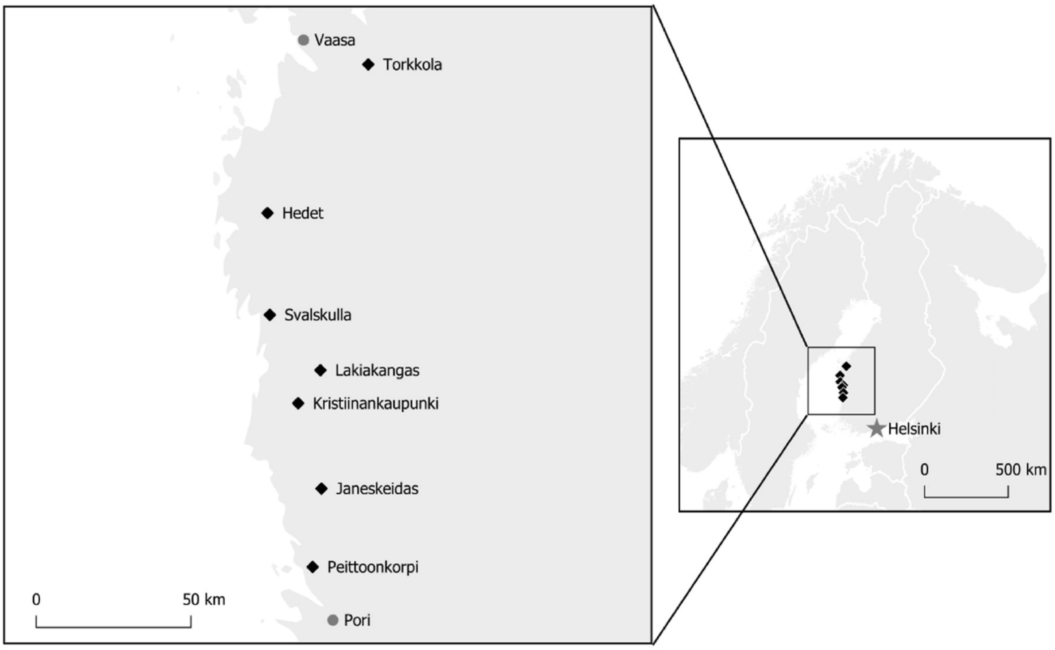

Fig. 1. Localisation of the seven study sites (black diamonds) and their position in relation to close major cities (grey dots) and the capital (grey star).

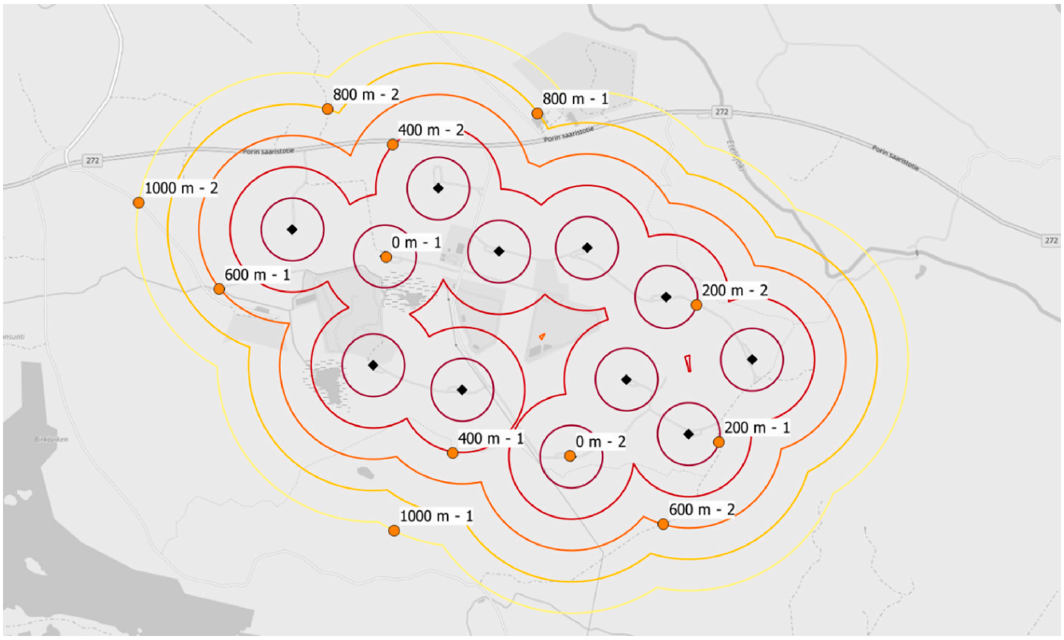

Fig. 2. Duplicate sampling points at a single wind farm. All points were sampled during the whole sampling period. Most of our sampling points were located on the perimeter of wind farms, especially for the “away” points, as it was easier to avoid the proximity of other turbines this way. Wind turbines are represented by black diamonds, acoustic recorders by orange dots. Circles around each turbine represent each sampling distance (200, 400, 600, 800 and 1,000 m). Background map is from Open Street Maps 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reliability of the auto-identification. Thus, we decided to validate all *E. nilssonii* calls with a confidence value superior to 0.2 provided by the software, and discarded the rest. Because the software is not reliable with the identification of species of the *Myotis* genus, and furthermore, the manual identification of their calls is complex, we decided to pool and analyse all *Myotis* calls as a group. Calls of other species identified by Kaleidoscope (*Pipistrellus nathusii*) were manually checked.

2.4. Statistical analyses

The estimation of bat abundance is not possible with acoustic monitoring. Therefore, we opted to assess bat activity at each site, using the positive minute as our unit of measure (Vasko et al., 2020). Here, each minute with at least one bat call is assigned as “positive” for bat activity. Then we pooled positive minutes per week because of the expected temporal variations in bat activity in the boreal zone, something that would be more visible with such pooling.

We analysed the number of positive minutes during one week as a response variable with two separate analyses. Both analyses were run independently for *E. nilssonii* and calls of *Myotis* spp., our most common species at our sites. We did not have enough calls from other species to run the models. First, we analysed whether there were calls recorded (presence) or not (absence) per site in a mixed model with binomial errors. Second, we analysed the number of positive minutes per recorder in a mixed model testing for the fit of the following distributions: (1) negative binomial, (2) zero-inflated negative binomial; (3) Poisson; (4) zero-inflated Poisson. Using the R package glmmTMB (version 1.1.4; Brooks et al., 2017), we compared the models with the chosen distributions using Akaike Information Criterion (AIC) and degrees of freedom (DF), showing that the negative binomial distribution, with week and distance as factors, fit the data best (Appendices A and B). It also showed that pooling the activity per week was best to fit the data.

The ID of Audiomoth recorders and the ID of wind parks were assigned as random effects in all models. Fixed effects were (1) recording time per recorder and per week (in minutes, with or without bat calls in it) standardised to a zero-mean (2) distance of the recorded calls to the wind turbine as a factor; (3) canopy cover as a factor with three classes and (4) week of the recording coded as a factor (1 to 16). The models were implemented in glmmTMB (Bolker et al., 2009; Brooks et al., 2017) in R 4.1.2 (R Core Team, 2021). The intercept of the models reflects the expectation at a distance of zero (i.e., at the wind turbine) in canopy cover [95 %>x > 50 %] for the average recording time. The models statistically take into account differences due to recording time (reflecting night length), habitat, seasonality (fixed effect: week) while the random effects take into account the non-independence of observations from the same recorder and from the same wind park. Hence, our primary interest is whether the models' estimates for the different classes of distance from the wind turbine (200 m, 400 m, 600 m, 800 m, 1,000 m) significantly differ from the expected value at the wind-turbine (distance = 0 m; the intercept). Significance of these contrasts were tested using a Z-test of the model estimates.

2.5. Habitat loss

We estimated the area avoided by bats per turbine, and for all current and planned wind power projects in Finland up to June 2022. Information on wind farms in the country is publicly available on the website of the Finnish Wind Power Association. We used the observed range of avoidance (800 m for *E.* nilssonii, 1,000 m for *Myotis spp.*; Fig. 3) to determine the area avoided around each turbine by each species or group of species. Then, we calculated the proportion of area impacted by the presence of turbines in Finland, for all current and planned turbines.

3. Results

Overall, we recorded more *E. nilssonii* activity than *Myotis* spp. at our sites, 37,541 positive minutes (4.79 % of total recorded time) and 4,857 positive minutes (0.62 % of total recorded time), respectively. We also recorded *P. nathusii* (200 positive minutes, 0.03 % of total recorded time). In addition, we did not see significant variation in presence and activity based on canopy cover, but we observed numerous significant variations in presence and activity depending on the week (Appendices C, D and E).

Using presence/absence data, our results indicated significant differences in species presence at differing distances from wind turbines (Fig. 3). For *E. nilssonii*, presence at 600, 800 and 1.000 m was significantly higher than presence at 0 m from wind turbines (Fig. 3). Presence of *Myotis* spp. was significantly higher at 800 and 1.000 m from wind turbines (Fig. 3).

Using activity minutes (i.e., the quantitative number of positive minutes), only activity at 800 m was significantly higher than activity at 0 m in *E. nilssonii* (Fig. 4). Activity of *Myotis* spp. did not differ from the intercept at any distance from wind turbines (Fig. 4).

The results of these models allowed us to estimate the cumulative area lost due to the presence of wind turbines in Finland, reaching 0.66 % and 1.03 % of the total area of Finland for *E. nilssonii* and *Myotis* spp., respectively, only for currently operating wind turbines (Appendix

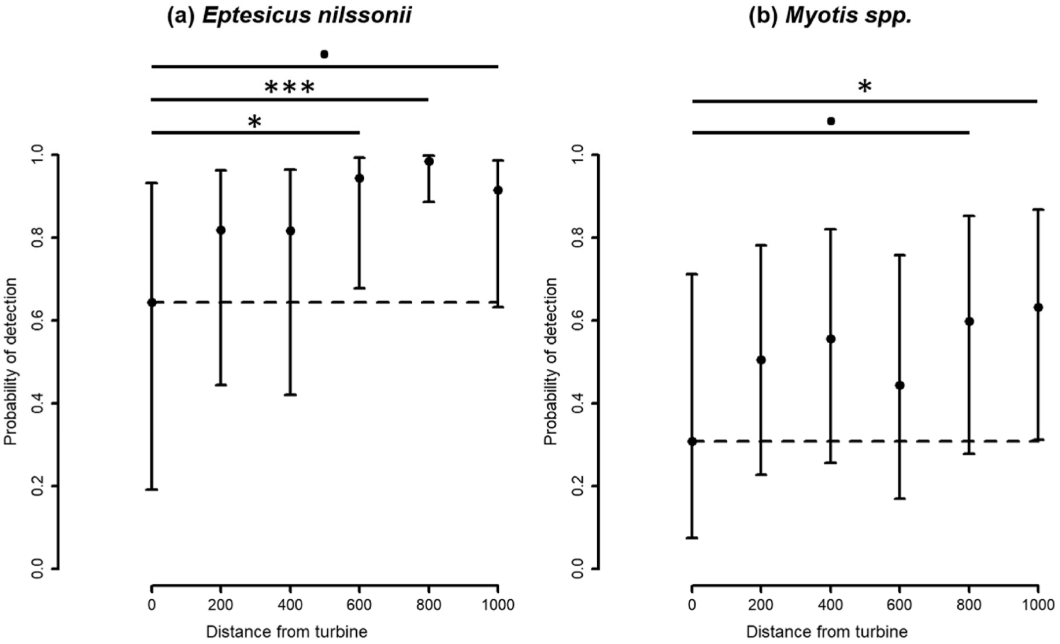

Fig. 3. The expected probability to record one or more echolocation pulses per week as a function of the distance from the wind turbine. Plotted are the back-transformed estimates of a mixed model with binomial error (Appendix C) for (a) *E. nilssonii* and (b) *Myotis* spp. The mixed model takes into account the effect of the recording time, seasonality and habitat differences (Appendix C). Error bars denote approximate 95% confidence interval computed as 2 times the SE of the estimate (Appendix C). Dashed line indicates the expectation at the wind turbine (distance of 0). Error-bars that do not overlap the dashed line indicate a significant deviation (see Appendix C for formal test statistics). A "***" symbol means a p value between 0 and 0.001, "**" for a value between 0.001 and 0.01, "*" for a value between 0.01 and 0.05, "." for a value between 0.05 and 0.1, " " for a value between 0.1 and 1.

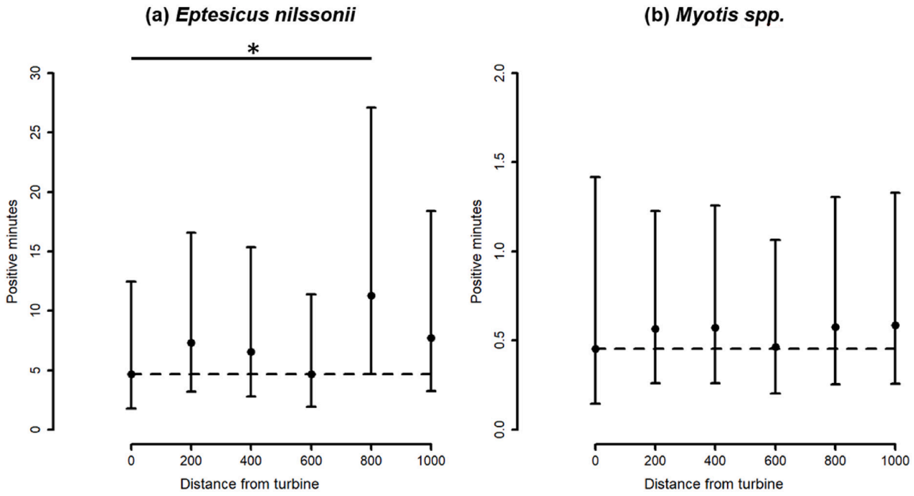

Fig. 4. The expected number of minutes per week when one or more echolocation pulses are recorded as a function of the distance from the wind turbine plotted as the back-transformed estimates of a mixed model with negative binomial error (Appendix D) for (a) *E. nilssonii* and (b) *Myotis spp*. The mixed model takes into account the effect of the recording time, seasonality and habitat differences (Appendix D). Error bars denote approximate 95% confidence interval computed as 2 times the SE of the estimate (Appendix D). Dashed line indicates the expectation at the wind turbine (distance of 0). Error-bars that do not overlap the dashed line indicate a significant deviation (see Appendix D for formal test statistics). A "***" symbol means a p value between 0 and 0.001, "**" for a value between 0.001 and 0.01, "*" for a value between 0.01 and 0.05, "." for a value between 0.05 and 0.1, " " for a value between 0.1 and 1.

F). If all projects ongoing are included, 4.38 % and 6.85 % of all Finland would be avoided by *E. nilssonii* and *Myotis* spp., respectively, only because of wind turbines (Appendix F).

4. Discussion

Our study is the first to investigate and demonstrate the avoidance effect (i.e., the avoidance of wind turbines or their surroundings by bats) in the forests of the European boreal biogeographic region, thus providing new data on the impacts of wind power on bats. Our study also shows the potential extent and consequences of this avoidance effect, i.e., the loss or fragmentation of vast areas of habitats normally used by bats.

Regarding overall bat presence and activity at our 84 sampling points, *E. nilssonii* was present over the largest number of sampling weeks, and was the most active species, which is not surprising as it is considered the most common species in Finland (Tidenberg et al., 2019). Despite being able to forage in open space, *E. nilssonii* is mostly active at low height, which implies our sampling design allowed us to obtain a comprehensive view of the species' acoustic activity (Blomberg, 2016). The *Myotis* genus comprises six species present in the country, including common species within the study region such as *M. daubentonii*, *M. brandtii* and *M. mystacinus* (Tidenberg et al., 2019; Vasko et al., 2020).

Our results show that the presence of both *E. nilssonii* and *Myotis spp.* are affected by the proximity of wind turbines: both taxa increase in presence with increasing distance from the turbine. These results indicate that the presence of wind turbines have a repelling effect on bats within a range of at least several hundred metres around each turbine. This is also the first time that avoidance is shown specifically for *E. nilssonii*. Results on the presence of this species at 800 and 1,000 m could indicate the tail end of the avoidance effect, and that at this distance from wind turbines, we could expect to see the unaffected acoustic activity level of this species. In contrast, we believe this is not the case of *Myotis* spp., and that avoidance could be effective at greater distances than sampled in our study.

As shown in Appendices C and D, presence and activity of bats in forests varies a lot during our survey period and correlates with the distinct variations in night length and darkness at the latitudes the study was conducted. The night is at its shortest and brightest during the summer solstice, leading *E. nilssonii* to utilise habitats offering the best cover and darkness, forests, in order to avoid predators (Rydell, 1989, 1991, 1992; Vasko et al., 2020). After the solstice, the nights grow longer and darker, and *E. nilssonii* progressively return to more open habitats (Ijäs et al., 2017; Rydell, 1989, 1991; Vasko et al., 2020). The second increase of activity at our sites in late summer and autumn could indicate swarming or dispersal behaviour of *E. nilssonii* (Ijäs et al., 2017). Despite *Myotis* spp. being considered as true forest bats in the boreal region (Vasko et al., 2020), our results indicate a temporal pattern similar to *E. nilssonii*. The second increase of activity would, similarly to *E. nilssonii*, indicate swarming behaviour or the beginning of the migration to winter roosts. At the moment, it is not clear why *Myotis* spp. activity increases around the solstice at our sites. The most plausible explanation for this would be the strong influence of *M. daubentonii* in our data, as it is the most common *Myotis* species in Finland, and the second most common species in Finland overall (Tidenberg et al., 2019). This species is known to strongly prefer wetlands for foraging and woodlands for roosting, so it is possible that we recorded calls during commuting, or that the species switches to forests to forage during the solstice period because lakes and rivers are too open and light (Vasko et al., 2020).

The avoidance effect could have ecological consequences for bats, primarily the loss of the habitats located both on their territory and near wind turbines (Rybicki and Hanski, 2013). Narrow- and edge-space foraging species - and even open-space foragers during specific periods of the year (Flaquer et al., 2009) - are strongly dependent on habitats such as forests and wetlands, or wooded linear networks for their commuting and feeding (Davidson-Watts et al., 2006; Entwistle et al., 1996; Rudolph et al., 2009), and can have small home-range, especially at high latitudes. Making these habitats and landscape features unavailable or degraded in quality, would impair the ability of these bats to easily forage in these habitats, or to fly between their roost and feeding territories through these affected areas. Depending on the layout of the wind farm, this can lead to the fragmentation of the habitat through virtual barriers that cannot be passed, or areas that are very complex to navigate. For example, within the wind farms studied here, the avoidance effect can be considered to form a no-fly zone of several square kilometres around each turbine, which bats could not use. When considering cumulative impacts, regions where the density of wind turbines is high, like the western coast of Finland, will have extensive areas of degraded habitats for bats. Our estimation of avoided area indicates that a relatively small area of Finland is impacted by wind turbines. We however postulate that the cumulative area is an underestimation, because we only included projects publicly known as of June 2022, and that many more projects are surely planned for the future. Therefore, the proportional area of Finland impacted will greatly increase in the years to come.

Very importantly, our results also indicate that also *Myotis* species are impacted by wind power plants, although they are not often considered as victims of operating turbines (Rodrigues et al., 2015). Moreover, areas from which bats are repelled because of wind turbines would no longer profit from the ecosystemic services provided by bats, such as feeding on pest insects (Aizpurua et al., 2018; Blažek et al., 2021; Burgiełł, 2018; Garin et al., 2019).

Investigation on the causative mechanisms contributing to the avoidance effect is direly needed. Two possible "main" causes are that bats are either avoiding wind turbines themselves, or are avoiding the area surrounding the turbines. Regarding the former, several hypotheses have been proposed. Barré et al. (2018) suggested the red lighting of wind turbines as a possible source of deterrence, as it has been shown that red-lit turbines are less attractive for bats than unlit ones (Bennett & Hale, 2014), and that red lights in general can repel bats (Barré et al., 2021; Zeale et al., 2018). However, red lighting could have the opposite effect on migratory bats and attract them (Voigt et al., 2018). Moreover, the distance at which bats react negatively to artificial lighting is very low (5–20 m) when compared to the range of the observed avoidance effect in our study or others (Barré et al., 2021; Zeale et al., 2018).

Noise emitted by the turbines has also been suggested as a possible cause for the deterrence (Barré et al., 2018), as some bat species, known as passive-listening bats, avoid foraging in noisy environments (Allen et al., 2021; Luo et al., 2015; Schaub et al., 2009). However, bats can hear sounds between approximately 10 and 200 kHz (Grinnell, 1995), whereas the dispersion of sound emitted by wind turbines in this frequency range (Katinas et al., 2016) is inferior to the observed distance range of avoidance in this study (Figs. 3 and 4) or in the literature (Barré et al., 2018; Guest et al., 2022). Therefore, it is not clear how noise emitted by turbines could deter bats at such a range.

A third hypothesis is correlated to the presence of insects at wind turbines: just like for bats, it has been shown that insects are attracted and killed by wind turbines, a phenomenon that could change their distribution or decrease their abundance around wind farms (Jansson et al., 2020; Rydell et al., 2010b; Voigt, 2021). We also suggest that the change in habitat created by the construction of wind turbines in forests could also deter insects in the area, therefore indicating that turbines can either attract or repel insects, depending on the scale, habitat and species, similarly to what Leroux et al. (2022) observed with bats. The abundance and composition of insect communities around wind turbines should be investigated at a great scale to determine whether and how their presence is affected by wind turbines. Finally, it has been suggested that the turbulence created by wind turbines downwind could affect the flight of bats. However, it is not certain that bats flying near the ground or in the vegetation could be impacted by the turbulence zone (Perrow, 2017).

The second main cause behind this avoidance effect, that bats are avoiding the area surrounding wind turbines, could be explained by the changes in habitats caused by the construction of the wind turbines. It is particularly true in the context of wind farms located in woodlands (like in our study), because the establishment of turbines in this habitat entails cutting large portions of forests for turbine pads, or the roads connecting them. This has for consequences the multiplication of open areas in a landscape usually more close, an opening that is unfavourable to certain species like *Myotis* spp. and would explain why they are avoiding the area around wind turbines. However, our results do not show an effect of tree cover percentage on bat activity at our sites (Appendices C and D), but it is possible that our terminology is not precise enough and tree cover should be measured more precisely at each sampling site. The same phenomenon has been proposed to explain the attraction of other species (edge-space foragers mostly) to wind turbines located in forests (Kunz et al., 2007). Investigating the avoidance effect on non-operating turbines in forest could help identify the origin of such an effect: the transformed surrounding area, or the wind turbines themselves.

Besides ecological consequences for bats in the long-term, our results add proof towards the necessary improvement in consideration and protection of bats in the context of wind power development not only in boreal Europe, but also across the whole continent, starting with wind power planning (Barré et al., 2018). However, wind farm siting in Finland is complex. The country is covered by woodlands to an extent of approximately 72 %, and an additional 15 % is occupied by water bodies and wetlands. This leaves only 13 % to open lands, which is consequently also where most of the populated areas are located (Corine Land Cover data). Because developers have to stay away from populated areas, wind turbines are seldom constructed in open areas, therefore the current preferred implementation is in woodlands (Asko Ijäs, personal communication, March 30, 2022), despite guidelines not recommending this (Rodrigues et al., 2015). Moreover, the agricultural landscape in Finland is still rather fragmented and wooded, with small forest patches or hedgerows that still constitute favourable habitats for bats. Therefore, there are challenges in keeping wind turbines away from woodlands of any size in order to avoid impacts on bats. The situation can be assumed to be similar in the other countries of the European boreal biogeographic region (Estonia, Latvia, Lithuania and Sweden) with similar landscapes predominated by woodlands (Gaultier et al. 2020).

This placement of wind turbines at a landscape-scale is also an argument in favour of improving the quality of impact assessment for bats in wind power projects in Finland. If wind turbines are to be built in woodlands, it must, at a bare minimum, be confirmed the site is not an important area for bats. Only thorough site-specific surveys for bat activity and roosting can adequately assess the use and importance of the site by bats, and of the impacts the project can have on them. These surveys should consider all bat species, not only those currently considered sensitive to wind power because of collision risks. However, we acknowledge that defining the importance of a site for bats in the boreal region is not easy, especially when based solely on bat activity, as levels of activity are different to the rest of Europe. Nevertheless, we believe that thanks to studies and monitoring programs conducted in the region, it should be possible to create a reference scale for activity levels, such as has already been done in other countries (Haquart, 2016; Lintott et al., 2018).

Above all, implementing wind turbines outside woodlands should always be preferred when possible and considered synonymous with lower impacts on bats. If not, other mitigation solutions can be used. If bats only avoid operating wind turbines themselves, curtailment could be considered as an effective method to reduce the avoidance, by stopping wind turbines when bat activity is predicted to be high on site, similarly to what is done to reduce collision risk (Behr et al., 2017; Gartman et al., 2016b). A risk which also exists in Finland, with the sensitive species *P. nathusii* (Rodrigues et al., 2015), present in the country during the autumn migration, especially on its coastline, and that could profit from curtailment during this period (Ijäs et al., 2017). In the case of bats avoiding degraded areas around wind turbines, curtailment would be useless to reduce this impact. In this case, a possible solution would be to increase the quality of habitats away from wind farms. However, it is considered as a compensation measure, which should be used as a last resort, after preventive planning of wind farms has been conducted to avoid or mitigate the potential avoidance effect and habitat loss. Compensation measures are hard to implement, and would require important forest areas to be improved in quality for bats, such as growing mature forests, which takes time, or offer different features (canopy structure, dead trees, etc.) as different bat species have differing preferences. All of these would be done without reducing at all the original impacts of the projects on bats or without guaranteeing that bats would just move to the improved areas. Therefore, we recommend careful planning and siting of wind farms as the best way to mitigate its impacts on bats.

Our study shows that one species, *E. nilssonii*, and one group of species, *Myotis* spp., avoid wind turbines or their surroundings. Other species are present within our study sites but the existence of an avoidance effect on them was not tested due to the lack of sufficient data. This is the case for *P. nathusii*, a migratory species that is abundant in Finland only for a few weeks during the end of summer. Therefore, we recommend further studies on this species and other migratory species present in Finland (i.e., *Pipistrellus pygmaeus*), to determine if they are affected by wind turbines in the same way as *E. nilssonii* or the *Myotis* species are, with a focus on wind farms located very close to the shoreline (<5 km) to maximise the chances of recording the species.

We also recommend that for future investigations, bat activity must be monitored on a broader range than 1,000 m around turbines, as the actual range of the avoidance effect is currently unknown and could be larger than currently observed here, especially for *Myotis* spp. A similar phenomenon has been observed with roads, with studies showing an impact on bats up to a distance of 5 km, but without information on whether the intensity of avoidance decreases after this distance (Claireau et al., 2019).

5. Conclusions

Our study provides evidence that *Myotis* species, and for the first time *E. nilssonii*, actively avoid wind turbines or their surroundings in a woodland context, and that the distances at which this avoidance occurs is dependent on the taxa. Long-term consequences for bats imply potential large loss of habitats that can directly affect commuting and foraging. This is also a new challenge for wind power development: as of now, this impact must be seriously considered when implementing new turbines in any kind of habitat favourable to bats. Moreover, impacts of wind turbine operation are not targeting only species prone to collision but also others, whether they fly at rotor height or not. In regard to these results, we call for improvements in impact assessment for bats, most specifically in Finland where bats are poorly considered, but more broadly in Europe.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was funded by the Societas Pro Fauna et Flora Fennica. We wish to thank Maïté Jacquot, Miika Kotila, Melissa Meierhofer, Kaisa Merimaa and Jorma Nurmi for their valued assistance in the field and Ville Vasko for help with Kaleidoscope.

Appendix A. AIC results for the *Eptesicus nilssonii* activity tested models. “dAIC” stands for difference in Akaike Information Criterion (AIC) from the minimum-AIC model, “df” is for degree of freedom. We can see that the zero-inflated negative binomial distribution, with weeks coded as a factor, has the highest df value and a very low dAIC.

Model	dAIC	df
Zero-inflated negative binomial, week as factor, distance as continuous	0.0	24
Negative binomial, week as factor, distance as factor	2.6	27
Zero-inflated negative binomial, week as factor, distance as factor	3.3	28
Zero-inflated negative binomial, week as continuous, distance as continuous	281.5	11
Zero-inflated negative binomial, week as continuous, distance as factor	285.7	15
Zero-inflated Poisson, week as factor, distance as factor	10740.0	27
Poisson, week as factor, distance as factor	12856.1	26

Appendix B. AIC results for the *Myotis* spp. Activity tested models. “dAIC” stands for difference in Akaike Information Criterion (AIC) from the minimum-AIC model, “df” is for degree of freedom. We can see that the zero-inflated negative binomial distribution, with weeks coded as a factor, has the highest df value and a very low dAIC.

Model	dAIC	DF
Zero-inflated negative binomial, week as factor, distance as continuous	0.0	24
Negative binomial, week as factor, distance as factor	5.3	27
Zero-inflated negative binomial, week as factor, distance as factor	7.3	28
Zero-inflated negative binomial, week as continuous, distance as continuous	376.5	10
Zero-inflated negative binomial, week as continuous, distance as factor	383.7	14
Zero-inflated Poisson, week as factor, distance as factor	1071.5	27
Poisson, week as factor, distance as factor	1345.0	26

Appendix C. Results of a mixed model with binomial errors on the presence (one or more calls) or absence (no call) per week of *E. Nilssonii* and *Myotis* spp. group. Intercept represents the presence at 0 m from the wind turbine during week 1 and with a tree cover under 50 % (representative of wind turbine area on our sites). A “***” symbol means a p value between 0 and 0.001, “**” for a value between 0.001 and 0.01, “*” for a value between 0.01 and 0.05, “.” for a value between 0.05 and 0.1, “ “ for a value between 0.1 and 1.

Species group	**Variable**	**Estimate**	**S.E.**	**Z**	**P**	
E. nilssonii	(Intercept)	0.590	1.014	0.582	0.561	
	total recorded time	0.004	0.001	7.269	0.000	***
Presence at	200 *m*	0.919	0.869	1.058	0.290	
	400 *m*	0.903	0.908	0.995	0.320	
	600 *m*	2.220	1.032	2.151	0.031	*
	800 *m*	3.575	1.054	3.393	0.001	***
	1,000 *m*	1.788	0.920	1.943	0.052	.
Presence when	tree cover [x > 95 %]	1.291	0.689	1.874	0.061	.
		−0.058	0.913	−0.064	0.949	

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Species group	Variable	Estimate	S.E.	Z	P	
	tree cover [95 %>x > 50 %]					
Presence during	week 2	0.803	0.676	1.188	0.235	
	week 3	2.617	0.796	3.288	0.001	**
	week 4	1.448	0.940	1.541	0.123	
	week 5	−0.330	0.682	−0.485	0.628	
	week 6	−0.335	0.827	−0.405	0.686	
	week 7	−3.802	0.763	−4.981	0.000	***
	week 8	−0.559	0.599	−0.934	0.350	
	week 9	−1.843	0.582	−3.168	0.002	**
	week 10	−0.772	0.588	−1.313	0.189	
	week 11	−1.360	0.583	−2.334	0.020	*
	week 12	−0.769	0.591	−1.301	0.193	
	week 13	0.200	0.580	0.346	0.730	
	week 14	20.120	5492	0.004	0.997	
	week 15	1.998	0.797	2.508	0.012	*
	week 16	1.862	0.758	2.457	0.014	*
Myotis **spp.**	(Intercept)	−0.804	0.856	−0.940	0.347	
	total recorded time	0.004	0.001	8.560	< 2e-16	***
Presence at	200 *m*	0.826	0.625	1.322	0.186	
	400 *m*	1.031	0.646	1.597	0.110	
	600 *m*	0.577	0.684	0.843	0.399	
	800 *m*	1.201	0.675	1.779	0.075	.
	1,000 *m*	1.348	0.667	2.021	0.043	*
Presence when	tree cover [x > 95 %]	−0.153	0.456	−0.335	0.738	
	tree cover [95 %>x > 50 %]	−0.859	0.645	−1.331	0.183	
Presence during	week 2	0.897	0.571	1.571	0.116	
	week 3	3.734	0.594	6.290	0.000	***
	week 4	2.275	0.671	3.389	0.001	***
	week 5	1.515	0.586	2.585	0.010	**
	week 6	−0.014	0.615	−0.023	0.982	
	week 7	−1.476	0.648	−2.279	0.023	*
	week 8	0.693	0.554	1.251	0.211	
	week 9	−2.196	0.647	−3.394	0.001	***
	week 10	−2.196	0.647	−3.394	0.001	***
	week 11	−1.917	0.623	−3.076	0.002	**
	week 12	−1.234	0.690	−1.788	0.074	.
	week 13	−1.710	0.552	−3.100	0.002	**
	week 14	−0.172	0.495	−0.347	0.729	
	week 15	0.958	0.496	1.932	0.053	.
	week 16	2.297	0.542	4.240	0.000	***

Appendix D. Results of a mixed model with binomial errors on the activity (in positive minutes) per week of *E. Nilssonii* and *Myotis* spp. group. Intercept represents the activity at 0 m from the wind turbine during week 1 and with a tree cover under 50 % (representative of wind turbine area on our sites). A "***" symbol means a p value between 0 and 0.001, "**" for a value between 0.001 and 0.01, "*" for a value between 0.01 and 0.05, "." for a value between 0.05 and 0.1, " " for a value between 0.1 and 1.

Species group	Variable	Estimate	S.E.	Z	P	
E. nilssonii	(Intercept)	1.544	0.488	3.162	0.002	**
	total recorded time	0.002	0.000	12.692	< 2e-16	***
Activity at	200 *m*	0.446	0.410	1.088	0.276	
	400 *m*	0.337	0.425	0.794	0.427	
	600 *m*	−0.006	0.446	−0.014	0.989	
	800 *m*	0.879	0.438	2.005	0.045	*
	1,000 *m*	0.501	0.433	1.158	0.247	
Activity when	tree cover [x > 95 %]	0.373	0.302	1.233	0.218	
	tree cover [95 %>x > 50 %]	−0.143	0.414	−0.344	0.731	
Activity during	week 2	1.477	0.240	6.161	0.000	***
	week 3	2.058	0.215	9.566	< 2e-16	***
	week 4	1.212	0.238	5.096	0.000	***
	week 5	0.075	0.237	0.318	0.751	
	week 6	−0.389	0.255	−1.525	0.127	
	week 7	−1.789	0.284	−6.301	0.000	***
	week 8	−0.476	0.253	−1.880	0.060	.
	week 9	−0.346	0.239	−1.450	0.147	
	week 10	−0.137	0.235	−0.582	0.561	
	week 11	−0.233	0.237	−0.983	0.326	
	week 12	0.107	0.247	0.433	0.665	
	week 13	1.000	0.221	4.535	0.000	***

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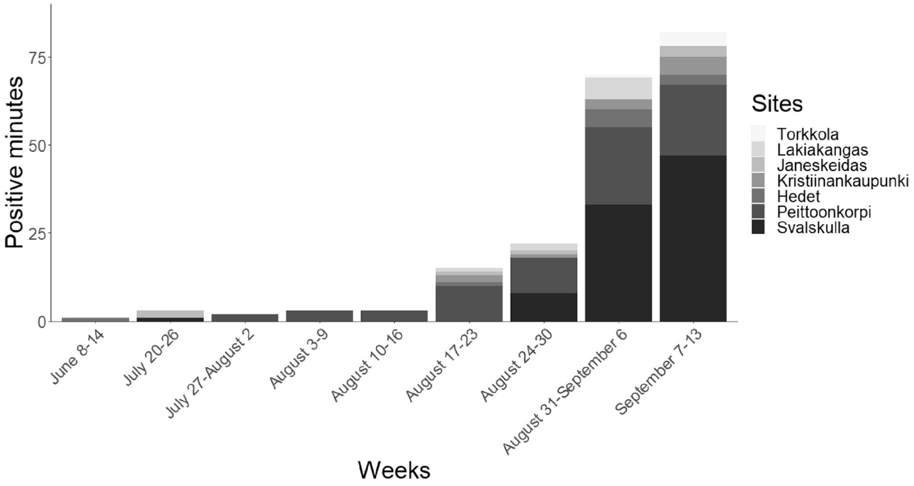
Species group	Variable	Estimate	S.E.	Z	P	
	week 14	1.745	0.221	7.889	0.000	***
	week 15	1.438	0.218	6.588	0.000	***
	week 16	1.833	0.222	8.273	< 2e-16	***
Myotis **spp.**	(Intercept)	−0.793	0.570	−1.391	0.164	
	total recorded time	0.002	0.000	10.869	< 2e-16	***
Activity at	200 *m*	0.222	0.387	0.573	0.567	
	400 *m*	0.234	0.394	0.595	0.552	
	600 *m*	0.023	0.416	0.054	0.957	
	800 *m*	0.239	0.410	0.582	0.560	
	1,000 *m*	0.260	0.409	0.636	0.525	
Activity when	tree cover [x > 95 %]	−0.217	0.280	−0.775	0.439	
	tree cover [95 %>x > 50 %]	−0.001	0.382	−0.003	0.998	
Activity during	week 2	1.948	0.314	6.211	0.000	***
	week 3	2.741	0.284	9.645	< 2e-16	***
	week 4	2.289	0.301	7.599	0.000	***
	week 5	1.382	0.306	4.509	0.000	***
	week 6	0.928	0.321	2.892	0.004	**
	week 7	0.302	0.342	0.885	0.376	
	week 8	1.230	0.333	3.696	0.000	***
	week 9	−0.905	0.395	−2.290	0.022	*
	week 10	−0.750	0.385	−1.951	0.051	.
	week 11	−0.772	0.385	−2.003	0.045	*
	week 12	−0.198	0.404	−0.490	0.624	
	week 13	−0.360	0.328	−1.097	0.273	
	week 14	0.813	0.297	2.734	0.006	**
	week 15	1.059	0.295	3.588	0.000	***
	week 16	1.875	0.294	6.384	0.000	***

Appendix E Activity of *Pipistrellus nathusii* in positive minutes, depending on the week and site. Sites are coloured based on their distance to the sea, with black being the closest and white the most distant to the sea.



Appendix F Cumulated habitat loss on studied bat species, for current and future wind power projects in Finland.

	E. nilssonii		*Myotis* spp.	
	km^2	Percentage of Finland area	km^2	Percentage of Finland area
Area per turbine	*2,01*	–	*3,14*	–
<u>Area for:</u>				
Operating turbines	*2235,81*	*0,66*	*3493,45*	*1,03*
Turbines under construction	*1584,37*	*0,47*	*2475,58*	*0,73*
Permitted turbines	*1109,86*	*0,33*	*1734,16*	*0,51*
Planned turbines	*9908,33*	*2,93*	*15481,77*	*4,57*
Cumulated:	***14838,37***	***4,38***	***23184,95***	***6,85***

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