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Research article

Long-term management practices successfully reduce bird-related electrical faults in a transmission grid increasingly used by white storks for nesting

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A R T I C L E I N F O

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A B S T R A C T

Bird nests on transmission lines can cause electrical faults which reduce service reliability. To address this problem, since the mid-90s, the Portuguese Transmission System Operator (TSO) has undertaken management actions to discourage white storks *Ciconia ciconia* from nesting in hazardous locations of the pylons. Here, we compiled and analyzed an 18-year series of data on electrical faults, TSO management actions to tackle these, and stork nests on transmission pylons in Portugal to: (a) determine the relative importance of bird-related faults over the total number of faults; (b) describe variations in bird-related faults across time (season of the year and time of the day); (c) describe spatial variations in bird-related faults and their association with the occurrence of white stork nests on pylons; and (d) analyze the trends, over the years, of the number of white stork nests on pylons, the TSO management actions and their effectiveness in reducing bird-related fault rates. Overall, birds accounted, on average, for 25.3% of the electrical faults in the transmission network, with the vast majority being attributed to white storks. The seasonal pattern of bird-related faults showed higher rates in April and in October–November. Faults occurred more often during the night period, when storks spend more time on the pylons. We found a positive spatial relationship between the electrical fault rate and the proportion of pylons with stork nests (and the correlated number of nests per 100 km of line). There was, however, considerable variation in the fault rates not explained by the stork nest variables, particularly during the non-breeding season. The TSO management actions (namely removal/translocation of nests in hazardous locations of the pylons, installation of anti-perching devices and provision of alternative nesting platforms) significantly reduced, as a whole, the annual number of bird-related faults between 2001 and 2018, despite the three-fold increase in the number of white stork nests on transmission pylons. A deeper understanding of how white storks use the transmission pylons outside the breeding season is needed, so that targeted management actions can be taken to reduce the remaining bird-related fault rates to residual levels.

1. Introduction

Transmission and distribution power lines play a critical role in the safe and reliable delivery of electricity to end-consumers. Overhead electricity networks are, however, vulnerable to electrical faults (i.e., disruptions in the flow of electricity) which may be temporary (when no equipment damage has occurred and the circuit is quickly restored through automated mechanisms), or permanent (when the fault causes a damage to the system that usually requires repair and, therefore, causes an interruption of service for customers) (Short, 2005).

Electrical faults may be triggered by equipment failures or environmental factors such as adverse weather conditions, contacts of cables with vegetation, wildfires, and animal interactions (Gomes-Mota et al., 2012; Wang, 2016). Animals are known to cause a large number of

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faults, which lead to economic losses and reduces the reliability of the electrical system (Bahat, 2008; EEE, 2005), in addition to killing or injuring animals from a wide range of species (Eaton, 2017; Katsis et al., 2018; Lehman et al., 2007). Reducing the socio-economic and conservation impacts of animal-related faults entails investigating their causes along with understanding their spatial-temporal patterns (Doostan and Chowdhury, 2019; Kankanala et al., 2015), in order to best target mitigation measures.

Birds are an important source of power outages in overhead transmission and distribution systems (Sundararajan et al., 2004a, 2004b). These are often caused by bird electrocutions which occur when a bird simultaneously makes contact with one phase and a grounded equipment or with two energized conductors with phase differences (typically large species perching on poles; Kagan, 2016). Electrocutions occur primarily in distribution lines (smaller power lines with lower voltages) but are much less common in transmission lines (larger power lines with higher voltages), especially on those ≥150 kV, because of the relatively large distance between conductors and conductors-to-ground (Bayle, 1999; Kolnegari et al., 2021; Loss et al., 2014). Nonetheless, in transmission lines, there are other bird-related electrical faults, namely because of the use of pylons for nesting (D'Amico et al., 2018; Jenkins et al., 2013). Bird nesting can interfere with electricity transmission through: (1) nest materials, that may fall and make contact with conductor cables, and (2) bird droppings, which can partially or completely bridge the air gap between the conductor and the structure ("bird streamers"), or contaminate insulators (reducing their efficiency and causing flashovers) (Liu et al., 2020; Polat et al., 2016; Rooyen et al., 2002). Surprisingly, and despite its importance for a deeper understanding of this human-wildlife conflict, variations in electrical fault rates as a function of the presence of bird nests in transmission pylons have rarely been explored before (Acklen and Campbell, 2008; Kolnegari et al., 2022).

White storks (*Ciconia ciconia*) are known to frequently use power lines for nesting (Infante and Peris, 2003; Janss, 1998; Taklaja et al., 2013). In Portugal, between 1984 and 2014, the proportion of white stork nests in electricity pylons increased from 1% to 25% of the whole national breeding population (Moreira et al., 2017). These nests can create an increased risk of faults (Taklaja et al., 2014; Zhou et al., 2009). Thus, the Portuguese transmission system operator (TSO) initiated in the mid-1990s a nest management program that entailed the removal or translocation of hazardous nests to nesting platforms installed in safe locations of (the same) pylons and the setting of anti-perching devices to discourage storks from nesting and perching in hazardous locations of the pylons, namely in the cross arms (above the conductors and insulators) (Gomes-Mota et al., 2014). The long-term effectiveness of this nest management program has however not been scientifically evaluated and, to our knowledge, neither have the effectiveness of similar mitigation programs (CIGRE, 2022). This is probably explained by the limited access to long-term datasets of bird-related electrical faults and TSO actions to tackle these, together with the lack of robust information on pylon colonization by nesting birds over time and space.

In this paper, we aimed to evaluate the spatio-temporal patterns of bird-related electrical faults and their possible drivers in the Portuguese transmission grid, over an 18-year period, as well as the management responses of the TSO and the resulting trends in the incidence of faults. More specifically, we: (a) characterize the relative importance of bird-related electrical faults (compared to other fault causes); (b) describe variations in bird-related faults across time (season of the year and time of the day); (c) describe the spatial patterns of bird-related faults at the national scale, and investigate their association with the occurrence of white stork nests on pylons; and, finally, (d) evaluate the trends over the years in the number of white storks nests on pylons, the TSO management actions and their effectiveness in reducing bird-related electrical faults.

2. Methods

Data compilation

Information related to electrical faults was gathered from a database managed by the Portuguese Transmission System Operator (REN - Redes Energéticas Nacionais, SGPS, S.A.). This company is responsible for the management of very high voltage power lines (national transmission grid; 150–400 kV) across the country, totaling ca. 8900 km of length in 2018 (REN, 2020). The minimum height of pylons ranges from 23 to 39 m, depending on the type, and the corresponding minimum distances between live conductors and cross-arms (i.e., the length of insulator strings) ranges from 2.0 to 3.75 m (Supplementary Fig. 1).

To contextualize the overall importance of birds in the universe of fault causes, we extracted from REN's database information on causes of all faults that have occurred in the period 2001–2018; these were classified by the company, based on field checks by REN technicians and weather information, on a total of 38 different causes. Following Gomes-Mota et al. (2012), we grouped them into five major categories: lightning, wildfires, fog or pollution, birds, and other causes. Then, for the subset of bird-related faults, we extracted for each fault information on geographical location, year, month and hour of day. To enable comparisons across time, we calibrated the number of bird-related faults (per unit of time) by 100 km of grid length (as the grid length increased).

To assign a geographic location to each event and estimate fault prevalence (expressed as number of faults per unit length and unit time), we used the "circuit" as the unit of analysis, as due to the construction and deactivation of power lines sections, assigning a fault to a certain power line section over the years was problematic. For example, following the construction of a substation in the middle of an existing power line section, faults that occurred before the substation (plus line breaking) could not be matched with the ones that occurred in the two new power line sections that were generated. Therefore, we defined a circuit as a line section featured by the absence of significant changes on length and configuration (wire voltage and pylons) in all its extension during its service period. For each circuit we calculated the average number of faults per 100 km of line and per year. The latter information was incorporated into a Geographical Information System (GIS) and centroids were calculated for each circuit using QGIS software (version 3.14) to produce a map with the spatial patterns at national level.

As we aimed to explore the links between the amount of electrical faults per circuit and its use by nesting white storks, we gathered information on counts of white stork's nests on every transmission pylon. These counts were obtained from aerial line inspections performed by REN on a yearly basis (Moreira et al., 2017). Therefore, for each circuit with identified bird-related faults, we estimated the average (i) proportion of pylons used for nesting, (ii) number of nests per 100 km, and (iii) number of nests per occupied pylon, between 2001 and 2018 (excluding 2011 and 2017, when there was incomplete coverage in nest counts). These three variables express slightly different information to explore whether the observed fault patterns across circuits were more associated to the proportion of pylons used (regardless of the number of nests), the overall density of nests (regardless of the number of pylons used), or the density of nests only in pylons that were used for nesting (as an index of nest aggregation).

In addition to the number of stork nests, we gathered information on the management actions undertaken by REN to tackle bird-related electrical faults, during the 1998–2018 period. These actions consisted in the yearly removal (with the authorization of the nature conservation authority) of nests in hazardous locations of the pylons (in the cross arm, above insulators and conductors), coupled with the placement of anti-perching devices (with a three-cup configuration that spins horizontally as wind passes through it; Fig. 1) to prevent storks from rebuilding nests on the same locations, and the provision of alternative nesting platforms in safe locations of the pylon. In pylons expected to be colonized by nesting storks, platforms and anti-perching devices are also

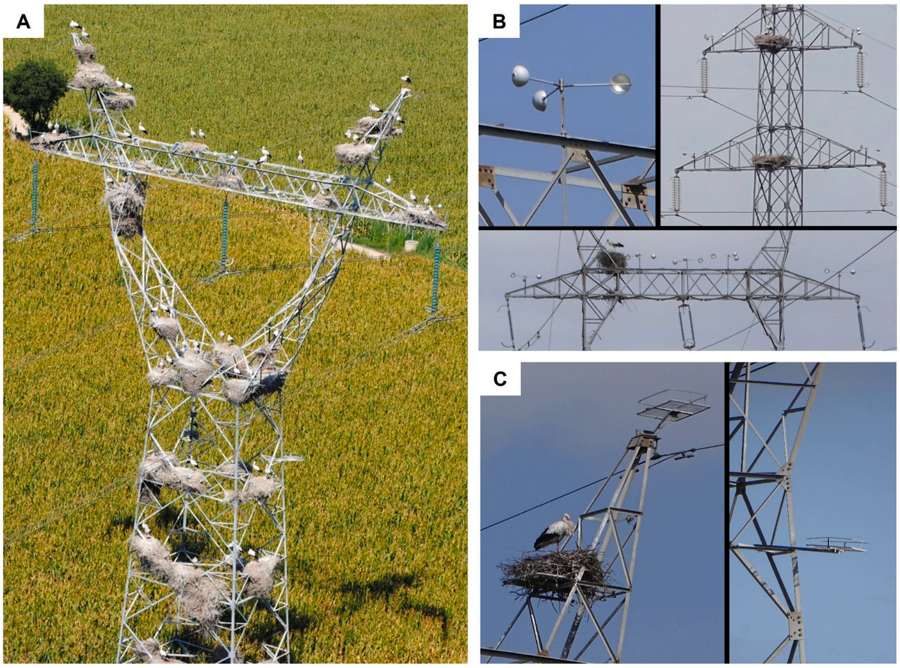

Fig. 1. A: Example of a REN's transmission pylon heavily colonized by nesting white storks (with more than 40 nests); B: The most used anti-perching device by REN, a metallic structure with three-cup configuration that spins horizontally with wind (both in detail and in the context of its installation in two types of pylons, to show their typical position, above insulators); C: Representation of the typical locations were nesting platforms are installed (on the mid-level or on top of the earth-wire support and on the sides of the pylon base).

preventively installed. The annual numbers of stork nests, existing anti-perching devices and artificial platforms were calibrated by 100 km of grid length to allow comparisons across years.

Statistical analysis

The relationships between the average number of faults by 100 km per year and the storks' nests explanatory variables, in each circuit, were explored using Generalized Additive Models (GAM), thereby accounting for potential nonlinearities in responses (Wood, 2006; Zuur et al., 2009). We performed these analyses using both all fault information and the subset corresponding to faults that occurred during the storks' breeding season (January to June), where we would expect more intense use of nests by storks and a better match between nest density and fault occurrence. Multicollinearity among explanatory variables was examined via Pearson's correlation coefficients. The variables "Average proportion of occupied pylons" and "Average number of nests per 100 km" were highly correlated (Pearson's $r = 0.86$, p-value <0.001), so the latter was excluded from the modeling as it had greater VIF (Variance Inflation Factor; Graham, 2003). The modeling procedure involved the fitting of a full model with the two uncorrelated variables ("Average proportion of occupied pylons" and "Average number of nests per occupied pylon"), followed by backward elimination of non-significant ($p > 0.05$) variables (Zuur et al., 2009). Model fit was evaluated by the adjusted r2 and the proportion of the null deviance explained. Two circuits were excluded from these analyses due to lack of stork nests information. Additionally, one circuit was considered an outlier and also removed, as it had a very high prevalence of faults (21.8 faults/100 km/year, compared with a median value of 0.93 faults/100 km/year for all the other circuits) but a small average number of nests (36.7 nests/100 km/year). This circuit was in service only until 2004.

The significance of the trend for the bird-related electrical fault prevalence (average number of faults per 100 km of line) and the Fault-Nest ratio (average number of faults per 100 stork nests on pylons) across the years were assessed by linear regression.

All analyses were performed using the statistical software R version 4.0.2 (R Core Team, 2020). GAMs were fitted using the mgcv package (Wood, 2006).

3. Results

Relative importance of bird-related faults

For a total of 3367 electrical faults that have been registered during the 2001–2018 period, the more prevalent cause was lightning (29.3%), followed by birds (25.3%), wildfires (16.2%), fog and pollution (9.7%), and other causes (19.4%). A total of 853 faults were attributed to birds, with the vast majority being white storks (99.7% of bird-related faults).

Seasonal and hourly variations in bird-related faults

There was no obvious pattern for fault prevalence across the year, but higher numbers were registered in April, October and November (Fig. 2). As for the time of the day, faults were overall more likely during the night, compared to daytime, and with the highest peak registered during the early morning period (from 5am to 7am) (Fig. 2).

Spatial variations in bird-related faults and possible drivers

Bird-related faults occurred in 59 circuits (ranging from 0.07 to 21.8 faults/100 km/year; median = 0.93; average = 2.1), and these were located mainly in central Portugal, mostly along the coast (Fig. 3). The backward-stepwise GAM selection using the nest-related variables resulted in just one variable being retained, the average proportion of pylons used for nesting, which explained a higher proportion of the variability in the number of faults when we focused the analysis on the storks' breeding season (adjusted $r^2 = 0.43$, $p < 0.0001$, deviance explained = 44.6%), compared with the analysis using all data (adjusted $r^2 = 0.30$, $p < 0.0001$, deviance explained = 32.1%) (Fig. 4).

Yearly trends in white stork population nesting on pylons, bird-related faults, and TSO management actions

The number of white stork nests in the REN grid has steadily increased over the years, from a minimum of 8.4 nests/100 km in 1998 to 34.9 nests/100 km in 2018 (Fig. 5). Contrarily, bird-related fault prevalence, although with yearly fluctuations, showed a significant declining trend in the 2001–2018 period (Pearson's $r = -0.648$, $p =$

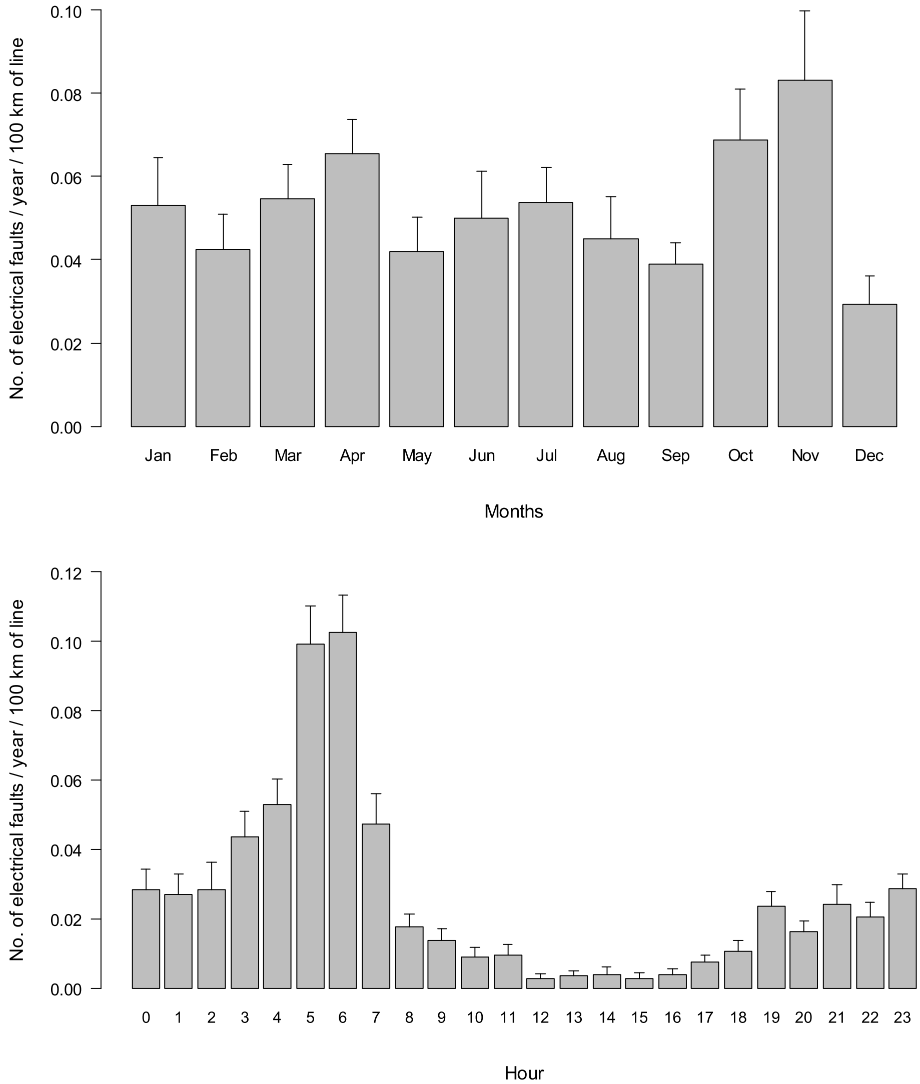

Fig. 2. Average number of electrical faults caused by birds (per 100 km of line) over months (upper graph) and time of day (lower graph) on REN grid over the 2001–2018 period. Error bars represent 95% confidence intervals.

0.004; Fig. 6). In fact, the ratio of the average number of electrical faults per number of stork nests declined steeply (Pearson's $r = -0.848$, $p < 0.001$; Fig. 6), with a decrease from 6.33 faults/100 nests in 2001 to 0.26 faults/100 nests in 2018 (ca. 95.9% reduction).

Over the 1998–2018 period, the number of anti-perching devices increased 17 times (from 5.8 to 101.6 devices/100 km), and the number of nesting platforms increased 4.5 times (from 8.4 to 38.5 platforms/100 km) (Fig. 5).

4. Discussion

Birds accounted, on average, for 25% of the electrical faults in the REN network, a value similar to what has been reported for other transmission grids around the world (Liu et al., 2020; e.g., Minnaar et al., 2012), with some exceptions (Taklaja et al., 2013). Therefore, birds do represent an important proportion of the problems that TSO have to manage. Most of the bird-related faults (99.7%) were attributed to white storks. Although this was expected, given the high level of pylon use shown by this species in Portugal, it should be acknowledged that some faults may have been assigned to storks by indirect evidence, such as the presence of nests in a section of a circuit and previous records of electrical faults attributed to white storks. Thus, results should be interpreted with caution as the assignment of faults to birds might have had some mistakes. Other studies have pointed out similar difficulties in the identification of bird-driven faults (e.g. Polat et al., 2016; Restani and Lueck, 2020;Taklaja et al., 2013). In any case, a study in Israel also concluded that wintering black storks accounted for up to 90% of the overall bird-driven outages in transmission lines (Bahat, 2008). Storks are therefore likely to represent a major source of bird-related electrical faults in their areas of occurrence, a consequence of their breeding/perching behavior and large liquid droppings. Faults caused by storks' electrocutions should however be negligible since, as expected for power lines with $\geq$150 kV, all bird mortality events in the REN's transmission grid (a database with $>$3400 records) result from collisions with the wires (Martins et al., 2021).

The annual pattern of bird-related faults follows roughly a bimodal distribution, with maxima occurring during the months of April and October–November. The first peak is consistent with the seasonal patterns of bird-driven faults in other transmission lines located in temperate regions (Liu et al., 2020; Maehl, 1996; Taklaja et al., 2013), and coincides with the breeding season, a period when nesting storks intensively use transmission pylons. The October–November peak suggests, however, that storks may use the transmission pylons also for roosting, a behavior documented in other stork populations during post-breeding and wintering periods (Bahat, 2008; Fernández-Cruz and Garrido, 2001). In the last two decades, the Portuguese white stork

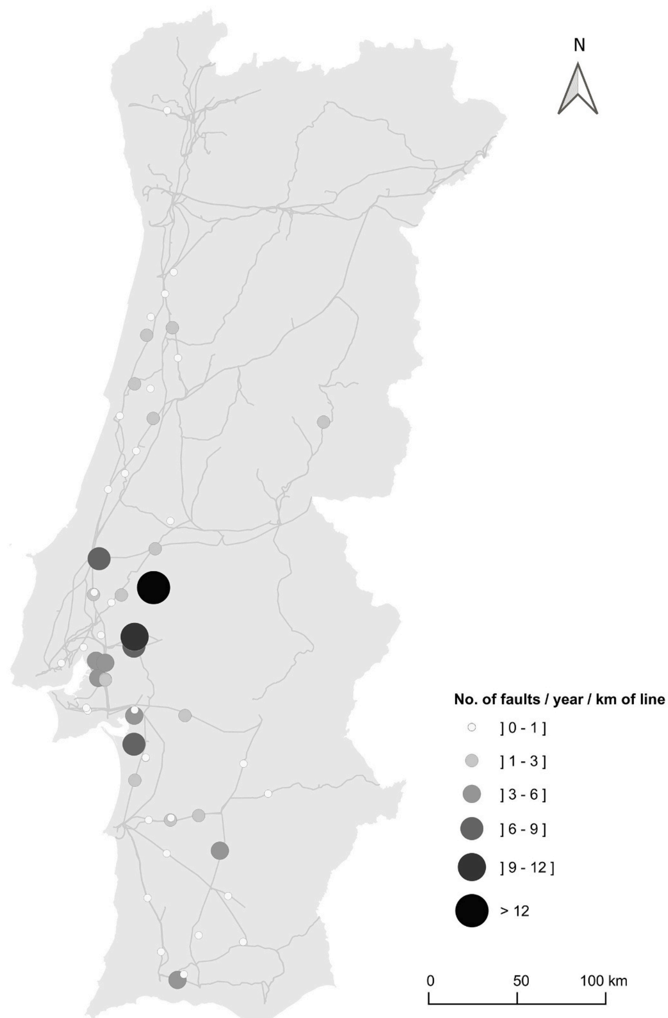

Fig. 3. Transmission (150–400 kV) power line grid in Portugal (in 2018; grey lines) and average number of bird-related electrical faults/year/100 km of line, for each circuit in which faults were registered, represented by centroids (dots).

population suffered a drastic change in their migratory behavior. The proportion of the Portuguese breeding population that stays in the country, rather than migrating to Africa, increased from 18% to 62% since the mid-1990s (Catry et al., 2017). During the non-breeding season, many of those resident storks concentrate in areas with high food availability, like wetlands, rice fields and landfill sites (Catry et al., 2017; Soriano-Redondo et al., 2021). Thus, we hypothesize that these individuals may use REN's transmission pylons (regarded as safe perching sites) for communal roosting. A large volume of droppings, together with wet weather conditions (because of autumn rains), make the occurrence of bird streamers more likely (Liu et al., 2020), which may explain the high number of electrical faults observed in October and November.

Resident white storks may be found in their nests throughout the day, regardless of the season, but their nest attendance is significantly higher during the night (Gilbert et al., 2016). This use pattern coincides with the hourly distribution of bird-related faults at REN lines, with the fault rate being higher during the night period. Nevertheless, in the early hours of the morning (between 5:00 and 07:00), there is a sharp increase in the fault rate. One hypothesis to explain this peak is the fact that birds excrete a large amount of droppings before taking-off for daily activities, which combined with accumulated water on insulators due to the condensation of air humidity, leads to an increased risk of flashovers (Burnham, 1995; Rooyen et al., 2002). A similar hourly pattern was observed in other transmission networks used by storks and other large birds (Ding et al., 2021; Liu et al., 2020; Taklaja et al., 2013), although different patterns were observed in other studies, with bird-driven faults increasing, for instance, after sunset or in the middle of the night (Acklen and Campbell, 2008; Bahat, 2008; Minnaar et al., 2012). In any case, our hourly pattern supports the results of other studies in transmission lines (Acklen and Campbell, 2008; Liu et al., 2020) which concluded that bird-related faults were caused mainly by droppings, and not by fallen nest material, as nest building is a daytime activity and faults occurred mostly during the night and early morning.

The spatial distribution of bird-related faults was positively associated with the proportion of pylons with stork nests and the correlated number of nests per 100 km of circuit. Thus, the prevalence of bird-driven faults is partly explained by the extension of the transmission grid colonized by storks and the overall number of nests in a circuit, rather than by the aggregation of nests in specific pylons. As expected, this relationship was stronger in the breeding season, when storks spend more time in the nests (Gilbert et al., 2016). However, there was considerable variation in the fault rates that was not explained by the stork nest variables, particularly in the non-breeding season. This provides further support to the hypothesis that the October–November fault peak may be caused by fecal streamers of resident storks that use transmission pylons for roosting, regardless of nest presence. Acklen and Campbell (2008) also found that, despite some correspondence between faults and nest locations (of raptors and ravens) in a 345 kV transmission line, at least half of the faults fell outside of any nest cluster. The authors concluded that the increased number of faults during the fall season was related to a known pathway for migrating raptors, and that fecal streamers were the likely main cause of faults. Non-breeding or roosting birds prefer to perch in the upper arms of the pylons (Bahat, 2008; Janss, 1998; Restani and Lueck, 2020), which increases the risk of fecal streamers and contamination of insulators. Thus, a deeper understanding of how white storks use the transmission pylons, even without nests, outside the breeding season (particularly in October–November) is required.

The TSO management actions effectively reduced the risk of bird-related faults. Although the number of white storks nesting in transmission pylons has increased threefold between 2001 and 2018, it did not impact the frequency of faults caused by storks, with the mean number of faults per 100 nests in the transmission grid being reduced ca. 95% along this period. The effectiveness of the three mitigation measures (nest removal/translocation; installation of alternative nesting platforms on safe locations, and installation of anti-perching devices on the cross-arms) could not, nevertheless, be evaluated separately. The future evaluation of their individual effect on discouraging pylon use by storks will be important given the annual investment made by the company in these measures, particularly in the installation of anti-perching devices.

5. Conclusions

In this study, we explored national-scale and long-term datasets (rarely available for research purposes) to evaluate the patterns of bird-related electrical faults, their relationship with the use of transmission pylons by nesting white storks and the TSO response to this human-wildlife conflict. Our results suggest that storks likely represent a major source of bird-related electrical faults in their areas of occurrence. More research is needed to explain the specific relationship between the electrical faults and circadian habits of storks, and their potential interactions with weather conditions (e.g., fog, morning mist). Nonetheless, observed temporal patterns revealed that bird-related faults are probably not explained solely by nesting-related activities and that storks may use the transmission pylons also for roosting. Future research should also examine how white storks use the transmission pylons outside the breeding season, so that targeted management actions can be taken to tackle the remaining bird-related fault rates.

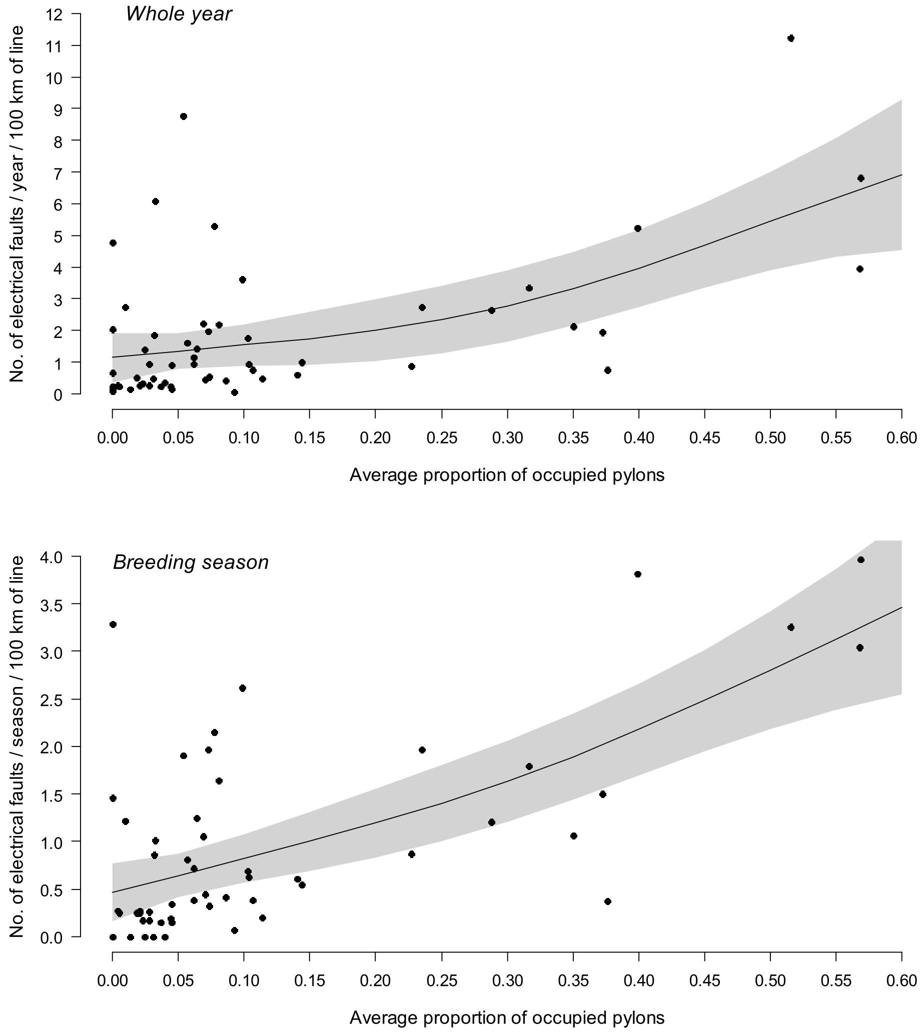

Fig. 4. Relationships between the average number of bird-related electrical faults per circuit and the average proportion of pylons with white stork nests, for the 2001–2018 period. Plots are show for overall faults (upper graph) and faults during the storks' breeding season (lower graph). Solid lines show the fit of the Generalized Additive Models and shaded areas the 95% confidence intervals.

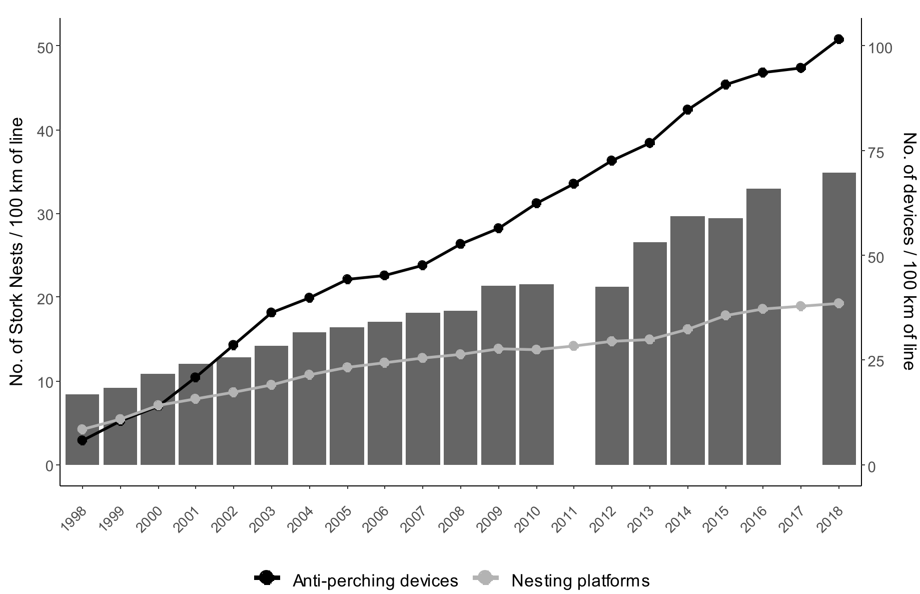

Fig. 5. Density of white stork nests (grey bars), anti-perching devices (black line), and nesting platforms (grey line) in the REN grid (in average number/100 km of line), between 1998 and 2018.

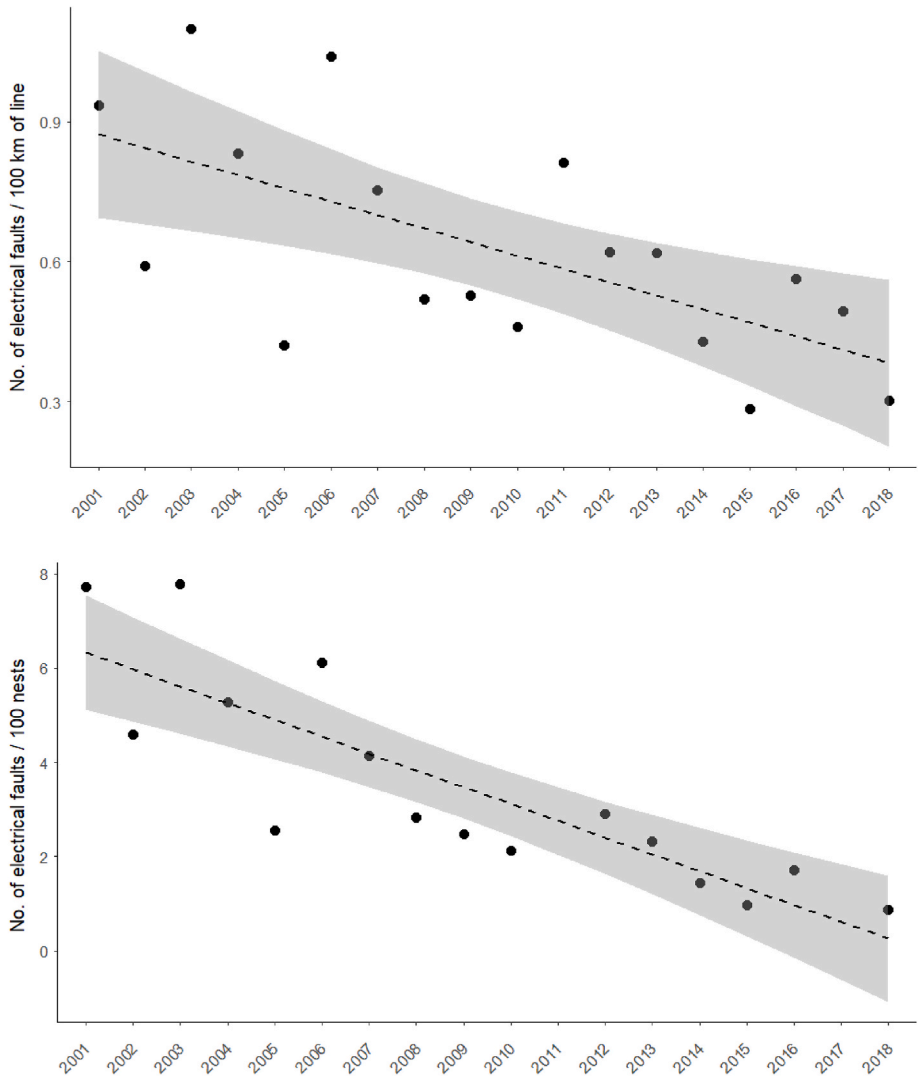

Fig. 6. Average number of bird-related electrical faults per line extension (upper graph) and per number of stork nests (lower graph) on REN grid over the 2001–2018 period. Dashed lines and shaded areas represent the linear regression lines and the 95% confident intervals of prediction, respectively.

The nest management program implemented by the TSO was effective in reducing bird-related electrical faults and, consequently, in increasing the reliability of the transmission grid. Because the nest management actions were carefully implemented (only nests in hazardous locations were removed and alternative nesting sites were provided), they did not inhibit white storks from continuing to breed on transmission pylons. This nest management program is, therefore, a good example of how energy infrastructures can be managed in ways that allow their use by birds, while ensuring service reliability.

Credit author statement

Francisco Moreira: Conceptualization, Methodology; Formal analysis; Writing – original draft; Writing – review & editing. **Ricardo C. Martins**: Conceptualization, Methodology; Formal analysis; Writing – review & editing. **Francisco F. Aguilar**: Methodology; Formal analysis; Writing – original draft. **António Canhoto**: Conceptualization, Data curation. **Jorge Martins**: Conceptualization, Data curation. **José Moreira**: Conceptualization, Data curation. **Joana Bernardino**: Formal analysis; Writing – original draft; Writing – review & editing.

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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116897.

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