



## Research article

# Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: A meta-analysis and guidelines for field studies

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## ABSTRACT

The expansion of overhead power lines worldwide challenges companies of energy transmission and distribution, regulators and environmental consultants, among other stakeholders, to effectively mitigate their negative impacts on wildlife. Wire-marking is currently the most widespread and recommended measure to reduce bird collisions with these infrastructures. Nevertheless, and despite its importance for a bird-friendly development of energy projects, there is still much uncertainty about what explains wire-marking effectiveness. We performed an extensive literature review and meta-analysis to evaluate the overall effectiveness of wire-marking in reducing bird collisions with power lines, including the possible influencing factors of power line voltage, habitat and type of device. We gathered data from 35 field studies across the world (which included 66 trials) assessing the effectiveness of wire-marking based on regular carcass searches beneath power lines. Overall, wire-marking reduced bird collisions with power lines by half (50.4%; 95% Confidence Interval Estimate: 40.4–58.8%), although this estimate of effectiveness is lower than the one reported in a meta-analysis performed in 2011. Despite the effort to include both peer-reviewed and grey literature studies in the present meta-analysis, the risk of publication bias could not be entirely excluded and may be still overestimating the true overall effect of wire-marking. High heterogeneity among the study outcomes hindered the power to detect clear moderating effects, with none of explanatory variables being statistically significant. Large between-study heterogeneity is (to some extent) explained by the variety of anti-collision devices available, wire-marking intensities used and ecological circumstances in which the experiments were carried out. Nonetheless, it may be also related to within-study methodological biases and reporting gaps in the existing field studies. Robust experimental designs (ideally using *Before-After-Control-Impact* approaches), comprehensive reporting of results and broad dissemination of study findings are needed to increase the statistical power of future meta-analyses. Ways to achieve these improvements in field studies are presented in detail. Their inclusion in future meta-analyses will increase the knowledge on the drivers of wire-marking effectiveness, which is critical to better inform decision-making processes and environmental management plans.

**1. Introduction**

Global demand for energy and the need to accomplish climate targets in the next decades will promote a rapid deployment of renewable energy generation and decarbonisation of the electricity grid (IRENA, 2017). The energy sector will continue, nevertheless, to rely on extensive networks of power lines to ensure the supply of electricity worldwide, despite their negative impacts on natural ecosystems (Biasotto and Kindel, 2018; D'Amico et al., 2018).

Bird mortality due to collisions with overhead wires has long been recognized as one of the most important negative impacts associated to both transmission and distribution lines (Bernardino et al., 2018). The most susceptible species to collision, in terms of expected

population-level impacts, seem to be “poor fliers” (due to their heavy body and/or low manoeuvrability), often habitat specialists with hazardous behavioural traits (especially flight height and flocking flight) and/or species with unfavourable conservation status (Bernardino et al., 2018; D'Amico et al., 2019; Jenkins et al., 2010). To address this problem, a wide variety of mitigation measures have been proposed and implemented over the last 30 years, such as underground cabling, optimization of power line routing and configuration, and/or wire-marking (Bernardino et al., 2018). The latter is currently the most widespread and recommended measure to reduce bird collisions with power lines (e.g. APLIC, 2012; SNH, 2016), mostly because it can be applied with minimal costs and engineering (compared to other mitigation strategies). Wire-marking consists in the attachment of

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different types of devices (e.g. spirals, plates, crossed bands, stripes or spheres) to the conductors and/or earth-wires, in an attempt to increase their visibility and divert birds from these obstacles.

Several field studies have been conducted to assess the effectiveness of this measure, although few have been published in peer-reviewed journals (e.g. Alonso et al., 1994; Barrientos et al., 2012; Sporer et al., 2013). In many occasions, results are only reported in grey literature documents (e.g. thesis and dissertations, book chapters, EIA monitoring reports, government/NGO publications), which are often scattered and difficult to access. Furthermore, estimates of wire-marking effectiveness are mainly done by comparing spatial and/or temporal variations in bird mortality rates (by collision with power lines), using three types of experimental design: *Control-Impact* (CI), *Before-After* (BA) and *Before-After-Control-Impact* (BACI). The validity of these approaches to measure mitigation effectiveness is based, however, on assumptions (like environmental similarity between *treatment* and *control* groups) which, if not fulfilled, affect the reliability of the conclusions (Christie et al., 2019).

Regardless of these constrains, the synthesis of evidence from existing studies is crucial to inform the decision-making process and future management actions by regulators, project developers, environmental consultants and other stakeholders. The first attempt to quantitatively summarize the effectiveness of wire-marking was done by Barrientos et al. (2011). Their meta-analysis showed that wire-marking had an overall positive effect in reducing bird collision rates by 55–94%. However, differences among types of anti-collision devices, power-line features and site-specific factors (apart from the number of species) were not tested. Since then, several more field studies have been conducted (or made publicly available) on this topic and, although evidence suggests that this mitigation measure works, there is still much uncertainty about what explains the large observed variability in wire-marking effectiveness.

Over the years, a wide range of devices and wire-marking intensities (i.e., combination of spacing between devices, number and position of wires marked, and portion of the power line span marked) have been implemented in power lines worldwide. Devices can be static (e.g. spirals) or, on the other hand, have dynamic features (e.g. rotating suspended plates), the latter being developed based on the general concept that devices with moving parts are more likely to draw birds' attention (Martin, 2011, 2010; Martin and Shaw, 2010). The shape, size and colour of the devices available on the market also varies a lot, with some devices also incorporating some type of luminescence (e.g. reflective or glow in the dark properties) (Bernardino et al., 2018). All these device characteristics are expected to influence the way birds perceive the power line and to have a moderating effect on wire-marking effectiveness (e.g. Anderson, 2002; Murphy et al., 2016a). Moreover, the effectiveness of each type of device is likely to be affected by the regional particularities of habitats and bird communities bisected by the power line, and its features (e.g. wires arrangement and height). Therefore, scientific evidence on what type of device should be implemented depending on the project characteristics and location, is particularly relevant for both electricity transmission and distribution operators.

Here, we carry out an updated meta-analysis of studies assessing the effectiveness of wire-marking in reducing bird collisions with power lines, including a number of studies published (or made available) since Barrientos et al. (2011), and pooling a large amount of data from grey literature. Our main objectives are to:

- 1) Estimate the overall effect of wire-marking on the rate of bird collisions and evaluate the impact of including grey literature in the estimated effectiveness;

- 2) Assess the moderating effect of site- and project-specific factors, namely habitat, power line voltage and type of device, on wire-marking effectiveness;
- 3) Identify the limitations of existing field studies and provide guidelines for future monitoring programmes of wire-marking effectiveness.

## 2. Methods

### 2.1. Literature review and inclusion criteria

Studies were first searched by examining the reference lists of three key systematic reviews on bird collision with power lines and its mitigation: Jenkins et al. (2010), Barrientos et al. (2011) and Bernardino et al. (2018) (see PRISMA flow diagram in Supplementary material 1). Full-text of potentially relevant articles, including grey literature (e.g. books, technical reports, dissertations and conference proceedings), were retrieved after screening of title and abstract. This initial list was then expanded through the screening of citations included in this first set of articles and so forth, until no new relevant articles were discovered. In addition, we conducted targeted searches (in Google Scholar and Web of Science search engines) of articles published after the systematic searching done by Bernardino et al. (2018), using the keywords “bird collision”, “power line” and/or “wire-marking”. No language or date restrictions were imposed to the search strategy. Articles unavailable online were obtained through contact of organizations and experts on the subject.

The preliminary literature search resulted in 58 full-text articles (hereafter called studies) of which 35 were considered eligible for the meta-analysis (see Supplementary material 2, Table S2.1). Only studies that assessed wire-marking effect based on measured rates of bird mortality by collision (e.g. not based just on flight behaviour characterization) were included in the analyses. Exclusion criteria were: 1) studies testing the effect of aviation balls or a mix of different types of devices (attached to a same wire); and 2) studies that did not report mean (or raw) counts of bird mortality and associated sample sizes, since these are necessary for calculating the weighted effect size (see below, 2.2 Effect size calculations and adjustments).

Whenever studies included results from multiple experiments (e.g. comparison of the effect of different types of wire-markers in separate sections of a power line, and/or testing of the same wire-marker in power lines located in different habitats), these were considered separate trials. Conversely, for studies reporting the effects of a same experiment for the entire bird community and/or separately for target species, we only included the results for the entire bird community (or consolidated the data from the different species/groups into a single trial), because data reported for target species are usually based on extremely low numbers of observed mortalities.

The final database comprised a total of 66 trials conducted in several countries (see Supplementary material 2, Table S2.2), although the majority of the trials was from Europe (n = 45, 68.2%), followed by North America (n = 11, 16.7%), Africa (n = 8, 12.1%) and, finally, South America (n = 2, 3.0%). Depending of the trial, one of following experimental designs was used: *Control-Impact* (CI; 39.4%), *Before-After* (BA; 33.3%), and *Before-After-Control-Impact* (BACI; 27.3%). CI trials provided a comparison of bird mortality between “impact” sites (i.e., power line sections with wire-markers) and “control” sites (i.e., without wire-markers). BA trials compared the same sections of a power line “before” and “after” the installation of wire-markers. In BACI trials, sampling is conducted at “impact” and “control” sites in simultaneous time periods, namely “before” and “after” implementation of the *treatment* (i.e., installation of wire-markers). CI or BA approaches rely on the assumption (often not verified) that environmental factors

affecting the mortality estimates do not significantly differ between “impact” and “control” sites, or between “before” and “after” periods, respectively. In BACI approach eventual differences between “impact” and “control” sites (not related with wire-marking effect) are accepted, as long as they remain the same between the “before” and “after” periods.

## 2.2. Effect size calculations and adjustments

The log response ratio ( $\ln R$ ), which is one of the metrics most commonly used in ecological meta-analyses (Nakagawa and Santos, 2012), was used to estimate the effect size (Hedges et al., 1999) and defined as:

$$\ln R = \ln \left( \frac{\bar{X}_T}{\bar{X}_C} \right) \quad (1)$$

where  $\bar{X}_T$  and  $\bar{X}_C$  are, respectively, the means of the response variable (bird mortality rate, expressed as number of bird carcasses/Km/search) for the *treatment* and *control* groups; i.e., in wire-marked and control sites (CI design), or before and after the installation of the wire-markers (BA design).

Our meta-analysis was inverse-variance weighted, meaning that variance was taken into account when calculating effect sizes for each study (Hedges et al., 1999). We calculated the variance of  $\ln R$  as:

$$\text{var}(\ln R) = \frac{s_T^2}{n_T \bar{X}_T^2} + \frac{s_C^2}{n_C \bar{X}_C^2} \quad (2)$$

where  $\bar{X}_T$  and  $\bar{X}_C$  are the means of the response variable on *treatment* and *control* groups, respectively;  $s_i^2$  ( $i = T, C$ ) is their sampling variance; and  $n_i$  ( $i = T, C$ ) is the sample size of each group.

Estimates of sampling variance (either for *treatment* or *control* groups) were often not reported in the studies. However, raw mortality rates are counts per time/area unit (e.g. number of death birds/Km/year). Therefore, this variable was assumed to be Poisson distributed, which means that its variance equals the mean (Koricheva et al., 2013). Hence, the variance of the response variable on *treatment* and *control* groups ( $s_T^2$  and  $s_C^2$ ) was always estimated by the observed mean of bird mortality ( $\bar{X}_T$  and  $\bar{X}_C$ , respectively), even on the few occasions that it was originally reported.

Thus, to estimate  $\ln R$ , and the corresponding variance for each trial, we extracted mean bird mortality rates and the corresponding sample size of wire-marked and control sites, and/or before and after the installation of the wire-markers. Few studies (15%) provided bird mortality estimates properly adjusted by the potential biases (e.g. scavenger removal, searcher efficiency), thus calculations of mean mortality rates were mainly based on raw data from carcass searches. Sample size was defined as the accumulated number of Kms surveyed in each site (i.e., the number of carcass searches times the number of Kms surveyed in each search).

Studies with BACI design are expected to achieve more robust results (compared to BA or CI designs; Christie et al., 2019), as it allows to account for differences between *treatment* and *control* groups not related to wire-marking. In such cases,  $\ln R$  was calculated as if it was a BA study (see Equation (1)), but the mean mortality rates registered “before” and “after” wire-marking ( $\bar{X}_C$  and  $\bar{X}_T$ , respectively) were first adjusted by the mortality rates registered in control sites (in the same corresponding periods). Whenever studies used BA or CI designs but data on bird flight crossing rates were also available for the same sites or periods, the ratio of crossing rates registered in *treatment* and *control* groups was used to previously adjust the mean mortality rate registered in the *control* group ( $\bar{X}_C$ ).

## 2.3. Extraction of moderators

Information on wire-marking intensities, study area and power line features was not always provided in detail by studies. To maximize the use of available data, we narrowed down the moderators to three variables: i) Voltage ( $<110\text{kV}$  and  $\geq 110\text{kV}$ ); ii) Habitat (Grasslands, Wetlands, Shrublands and Forest-farmland mosaics); and iii) Type of device (Small spirals, Large spirals and Flappers).

Power line voltage is a binary moderator that aims to embody a set of voltage-related features, such as the pylon height, thickness of conductors, presence/absence of earth wires, distances between different conductors and between conductors and earth wires, and placement of wire-marking devices (see Supplementary material 3). We considered two voltage levels, below and above 110kV, which can be generally considered distribution and transmission power lines, respectively, although the voltage threshold between these categories is variable across countries (CIGRE, 2018).

Habitat is a four-level moderator with categories defined based on the main characteristics of the landscapes bisected by the power lines: (1) Grasslands - open and rather flat areas with cereal farmlands and/or extensively grazed grasslands; (2) Wetlands - areas permanently or temporally flooded, such as lakes, rivers and estuaries, marshes and coastal lagoons; (3) Shrublands - semi-arid areas dominated by grassy, low-shrub vegetation; and (4) Forest-farmland mosaics - Native forests and/or tree plantations, interspersed with agricultural areas (often with trees) and/or occasional shrubs.

Wire-markers were categorized in three main types, depending mainly on their size and static/dynamic features: (1) Small spirals - static devices with spiral shape, single-side attachment (to the wires) and small dimensions (20–35 cm long, 6–18 cm in diameter) - also called “pigtailed”; (2) Large spirals - static devices with spiral shape, double-side attachment (to the wires) and large dimensions (60–100 cm long, 20–35 cm in diameter) - also called “swan flight diverters”; and (3) Flappers - devices with moving parts (due to wind action), including clamps with rotating planes or discs (e.g. Firefly) and devices with relatively limited dynamics (e.g. crossed bands, RIBE and other stripes, as well as clamps with suspended non-rotating plates or discs).

## 2.4. Statistical analysis

The analysis was carried out in R statistical computing language (R Development Core Team, 2018), using the *metaphor* package (Viechtbauer, 2010). To quantify heterogeneity among effect sizes, we fitted three-level random-effects models using the restricted (or residual) maximum likelihood (REML) estimation approach (Koricheva et al., 2013; Nakagawa and Santos, 2012). All fitted models contained the effect size ( $\ln R$ ) as the response variable weighted by its inverse-variance (Borenstein et al., 2009), and “trial ID” and “study ID” as random factors (Assink and Wibbelink, 2016). Random effects were included at trial-level to account for the potential effect of unreported covariates (that may have contributed to differences in effect sizes); and at a study-level to account for non-independency between values extracted from the same study (Nakagawa et al., 2017).

Using the multi-level models described above, we started by fitting a random-effects model to the complete dataset ( $n = 66$ ). Normality assumption and outlier detection were assessed through graphical residual analysis (Viechtbauer and Cheung, 2010). Five cases (7.5%) were defined as outliers and excluded from the dataset ( $n = 61$ , see Supplementary material 2, Table S2.2), as these extreme values are likely explained by study limitations and may have a disproportionate influence on the analysis. The random-effects model was then

refitted to estimate the overall weighted-mean effect size of wire-marking, accompanied by its 95% Confidence Interval Estimates (CIE). Heterogeneity was assessed by inspection of forest plots and Cochran's Q statistics (Nakagawa and Santos, 2012). Total heterogeneity was then partitioned into the proportion of variance explained by the random factors in the model (between- and within-study heterogeneity), and residual error variance (within-trial heterogeneity). Potential publication bias was assessed in three different ways: (1) visual examination of the funnel plot of raw effect sizes ( $\ln R$ ) against its inverse variance (as a proxy for sampling effort) (Sterne and Egger, 2001); (2) performance of Egger's regression test applied to model residuals, accompanied with their original variance (Egger et al., 1997; Nakagawa and Santos, 2012); and (3) comparison of weighted average effect sizes estimated solely based on peer-reviewed studies, *versus* grey literature.

Next, we investigated if heterogeneity between trials could be partially explained by the compiled moderators. We started by fitting three separate univariate mixed-effects models to the subset of trials with complete information for each candidate moderator: voltage ( $n = 58$ ), habitat ( $n = 52$ ) and type of device ( $n = 58$ ). The significance of fixed effects was determined using Wald-type statistics with asymptotic chi-square distribution (Koricheva et al., 2013). Then, we conducted a multivariate model selection analysis based on the subset of trials with complete information for all moderators ( $n = 47$ ). We used *glmulti* R package (Calcagno and de Mazancourt, 2010) to automatically fit all possible model combinations involving the three moderators, compare all candidate models and rank them based on their corrected Akaike's Information Criterion (AICc) value. The significance of each moderators in equally-plausible models (i.e., models with value differing less than two units from the higher-ranked model) was tested using a likelihood ratio test, and moderators were dropped from the final model when not significant. Fixed and random effects were estimated through maximum likelihood, to allow a meaningful comparison between models (Koricheva et al., 2013).

Finally, a sensitivity analysis was conducted to assess the robustness of the meta-analytic findings, which included the repetition of the primary analysis with altered datasets (Bown and Sutton, 2010), namely: (1) "Calibrated" - exclusion of trials perceived to be of lower quality (i.e., using BA or CI designs); (2) "Sample size  $\geq 30$ " - exclusion of trials with low sample size (i.e., No. of Accumulated Kms  $< 30$ , either for *treatment* or *control* groups); (3) "With outliers" - inclusion of trials identified as outliers; and (4) "Without influential cases" - exclusion of influential cases identified through Cook's distance statistics (Cook and Weisberg, 1982; Viechtbauer and Cheung, 2010). See Supplementary material 5 for more details about the rationale behind and methods used in the creation of the altered datasets.

Whenever appropriate, estimated effect sizes ( $\ln R$ ) and associated 95% CIE were transformed into percent reduction in bird collision rate (that is,  $[(1 - e^{\ln R}) \times 100]$ ), for easier interpretation of results.

### 3. Results

#### 3.1. Overall size effect and publication bias

Overall, wire-marking had a significant (positive) effect on reducing bird collisions with power lines (Fig. 1). The overall estimated log response ratio ( $\ln R$ ) was  $-0.70$  (95% CIE:  $-0.89, -0.52$ ), corresponding to an overall wire-marking effectiveness of 50.4% (95% CIE: 40.4–58.8%) in reducing bird collision rates with power lines. There was, however, significant amount of (residual) heterogeneity with respect to effect sizes ( $Q = 480.5$ ,  $df = 60$ ,  $p < 0.001$ ; see Supplementary material 4, Table S4.1). Most of the heterogeneity was explained by variance within- ( $I^2_{(level\ 2)} = 49.6\%$ ) or between-studies ( $I^2_{(level\ 3)} = 41.3\%$ ), rather than within trials ( $I^2_{(level\ 1)} = 9.1\%$ ). The mean effect sizes of the 61 trials included in the meta-analysis ranged between  $-2.36$  and

$0.72$ , which means that the reduction in bird collision rates varied between 90.5% and  $-104.8\%$  (Fig. 1).

Sensitivity analyses were performed, and the results remained similar after (1) removing studies with lower samples sizes (i.e., number of accumulated Kms  $< 30$ , either for *treatment* or *control* groups) and/or weaker experimental designs (namely, CI or BA designs), (2) excluding influential cases, and (3) re-including outliers (see Supplementary material 5, Table S5.1). The corresponding overall estimated  $\ln R$  ranged between  $-0.64$  and  $-0.81$ , which corresponds to a reduction in bird collision rates ranging between 47.0 and 55.4%.

There was no evidence of publication bias in the meta-analysis (Egger's regression test result:  $z = -0.50$ ;  $p = 0.61$ ), which is consistent with the apparent symmetry of the funnel plot (Fig. 2). However, if only peer-reviewed studies had been included in the meta-analysis ( $n = 12$ ), the overall estimated reduction in bird collision rate would be of 56.4% (95% CIE: 29.3–73.2%), which corresponds to an increased estimate of wire marking effectiveness compared to the one estimated solely based on grey literature (48.7%; 95% CIE: 37.7–57.2%) (Fig. 2).

#### 3.2. Moderators of wire-marking effectiveness

Univariate analyses revealed that none of the moderators had a significant effect on wire-marking effectiveness (Voltage:  $Q_M (df=1) = 0.2$ ,  $p = 0.63$ ; Habitat:  $Q_M (df=3) = 3.6$ ,  $p = 0.31$ ; and Type of device:  $Q_M (df=2) = 2.2$ ,  $p = 0.32$ ; see Supplementary material 4, Table S4.1). These findings were corroborated by the multivariate analysis, with two models fitting the sub-dataset equally well (Null model: AICc = 91.1, Akaike weight = 0.38; *versus* Model with Habitat as single-moderator: AICc = 91.6, Akaike weight = 0.29) (see Supplementary material 4, Table S4.2). The likelihood ratio test showed no significant differences between both models ( $p = 0.06$ ), so the null model was selected. The test for residual heterogeneity ( $Q_E$ ) was significant for all mixed-effects models (see Supplementary material 4, Table S4.1), indicating that variability among the effect sizes might be explained by (unaccounted) moderators. Once again, all meta-analytic findings were generally consistent with the ones achieved in the sensitivity analyses (see Supplementary material 5, Table S5.2).

Despite its non-significance as a moderator, all types of devices significantly decreased bird collisions with power lines, with a tendency for flappers to be more effective than spirals (either small or large) (Fig. 3). Wire-marking also appears to be slightly more effective in wetlands, compared to the other habitat categories, and in distribution lines ( $< 110$  kV), compared to transmission lines ( $\geq 110$  kV) (Fig. 3).

## 4. Discussion

#### 4.1. Overall size effect and publication bias

The results of our meta-analysis corroborate the general perception that wire-marking is effective in reducing bird collisions with power lines (e.g. APLIC, 2012; Jenkins et al., 2010; Williams et al., 2018). The estimate of the overall mean effect size shows that the number of bird collisions was reduced almost by half (50.4%; 95% CIE: 40.4–58.8%) in marked power lines, after diverter installation and/or compared to controls. Although this is a substantial reduction, the effectiveness estimate is considerably lower than the one estimated by Barrientos et al. (2011) (78%; 95% CIE: 55–94%), who performed the first meta-analysis on the topic. The difference in the results is probably explained by: (1) the additional number of studies and, consequently, number of trials included in the present study; and (2) the latest methodological advances in biological meta-analysis, such as accounting for non-independency between experiments from a same study (Nakagawa et al., 2017; Nakagawa and Santos, 2012).

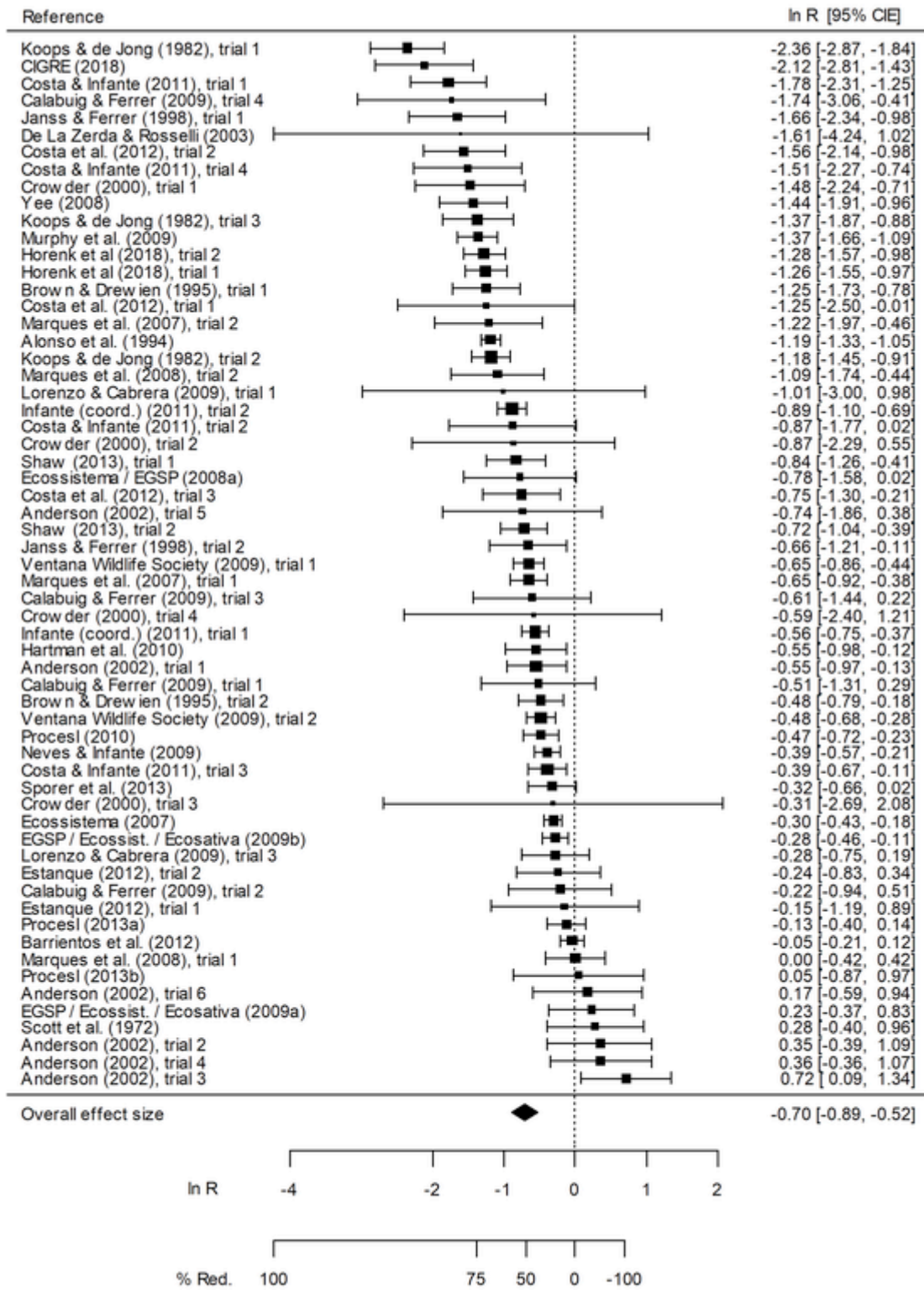


Fig. 1. Forest plot of (ordered) effect sizes and 95% Confidence Interval Estimates (CIE) of each individual trial (n = 61). The “diamond” on last row shows the overall mean effect size (central tips of diamond) and associated 95% CIE (lateral tips of diamond) estimated based on the random-effects model. Primary and secondary x-axis represent the log response ratio (*ln R*) and percent reduction in bird collision rates (% Red.), respectively. Negative values of *ln R* indicate that wire-marking had a positive effect in reducing bird collisions with power lines, positive values indicate the opposite (increased collision rates). *ln R* = 0 means no effect.

We found no evidence of clear publication bias within our systematic review, which is probably explained by the high number of trials retrieved from grey literature (76%), compared to trials published in peer-reviewed journals (24%). Still, we cannot exclude the

possibility of such bias. First, the estimated wire-marking effectiveness was lower in grey literature studies, compared to the one estimated in peer-reviewed studies. Second, many studies are carried out internally by energy companies or under the scope of EIA processes, and only

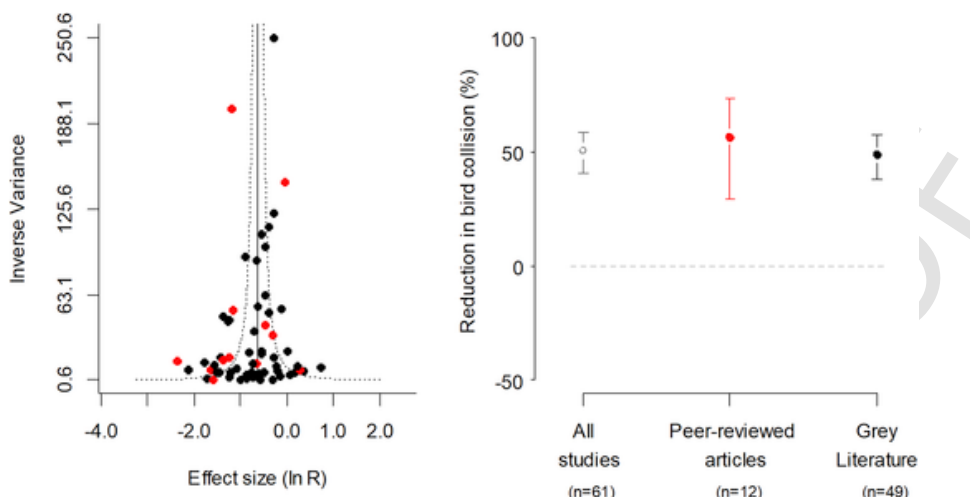


Fig. 2. Funnel plot of effect sizes ( $\ln R$ ) of each individual trial from the complete dataset (on the left) and overall percent reduction in bird collision rates ( $\pm$  95% Confidence Interval Estimates), estimated based on trials retrieved from peer-reviewed articles, grey literature studies or all types of studies (on the right). Red and black dots indicate, respectively, the effect sizes retrieved from peer-reviewed articles and grey literature. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

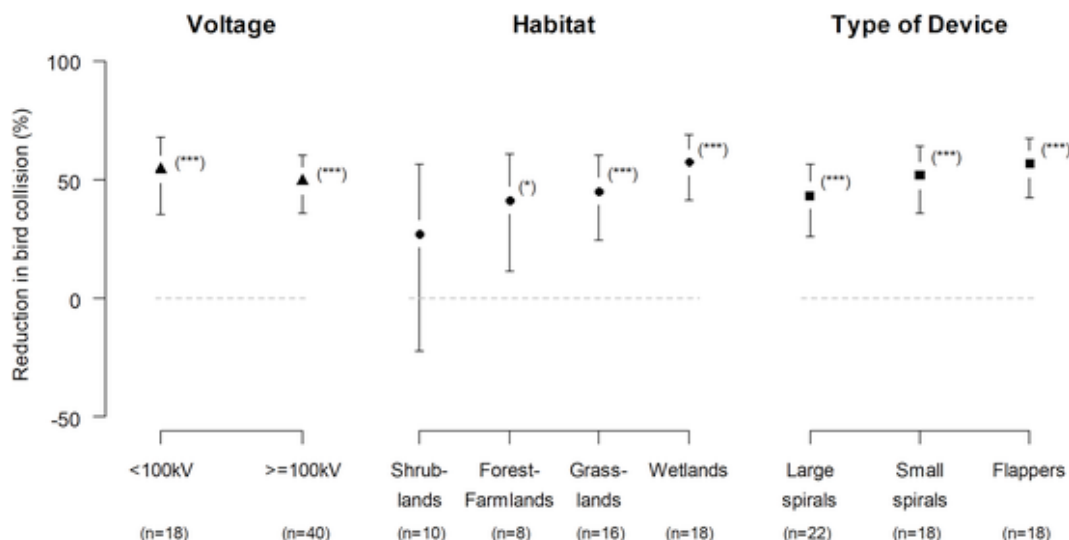


Fig. 3. Effectiveness of wire-marking in reducing bird collision rates (mean/ $n R \pm$  95% Confidence Interval Estimates) depending on power line voltage, habitat and type of device, estimated by the univariate mixed-effects models. Significance levels (\* indicates  $p < 0.05$ , and \*\*\* $p < 0.001$ ) near the effect size symbols denote a significant difference from zero (no effect).

reported in grey literature that is difficult to access. And, third, energy companies tend to be less supportive of publishing studies with negative results (i.e., showing that the mitigation measure was not effective and/or highlighting the study limitations). This suggests that the true wire-marking effectiveness may probably be lower than the one estimated in this study.

Concerns about the quality of grey literature are often raised, usually due to limitations on study design and relatively low sample sizes (Lajeunesse, 2013). This was not the case for several grey literature studies compiled in the present meta-analysis (e.g. Calabuig and Ferrer, 2009; Marques et al., 2007). Nonetheless, low statistical power of individual studies was fairly addressed in the weighted meta-analysis conducted, as studies with a large sampling error contributed less to the estimates of overall effect (using the inverse variance of each effect size as a weight) (Lajeunesse, 2013). Conversely, well-conducted studies with tight control of measurement variation and/or larger sample sizes contributed more to estimates of effect size, independently of where they were published.

#### 4.2. Moderators of wire-marking effectiveness

To the best of our knowledge, no previous study has conducted a meta-analysis to quantify the moderating effect of project- and site-specific factors on wire-marking effectiveness. None of the moderators (type of device, habitat or power line voltage) was found significant in our meta-analytic models. The lack of a statistically evidence towards a significant result does not necessarily mean that these three moderators have no influence on wire-making effectiveness, being most likely a consequence of the high heterogeneity (i.e., variation of effect size estimates) among the pooled studies, as the power to detect moderator effects in meta-analyses is largely determined by the degree of (residual) heterogeneity present in the dataset (Hempel et al., 2013). This large variability might be explained by within-study methodological biases (see next section, 4.3 Study limitations), but also by confounding variables that could not be examined independently. For instance, a limited number of studies provided comprehensive information about: (1)

the wires arrangement and, consequently, the number of collision levels for birds; (2) which wires were marked; and/or (3) what was the spacing between markers. Thus, neither power line configuration nor wire-marking intensity could be examined as separate moderators of wire-marking effectiveness.

We found a weak evidence that devices with moving parts (here called “Flappers”) may be more effective than static devices (like spirals), as hypothesised by Martin (2010, 2011) and Martin and Shaw (2010). According to these authors, frontal/binocular vision in birds is primarily concerned with near tasks (e.g. control of bill in foraging, chick provisioning, nest building) and more tuned for the detection of movement (rather than spatial detail); thus, devices with moving parts are more likely to draw birds’ attention. There were, however, device characteristics which could not be evaluated in the present meta-analysis, due to the lack of detailed information in the studies and/or small number of trials available for each factor level. These include colour (e.g. all white, grey, red or mix of colours), luminescence (e.g. reflective or glow-in-the-dark properties) and type of flapper (e.g. Fireflies, suspended discs, crossed bands), expected to influence the way birds perceive the power line during daylight, but also at night or in low visibility conditions (e.g. during migration periods) (Murphy et al., 2016a).

#### 4.3. Study limitations

The limitations of our review and meta-analysis are partially related to reporting gaps in the existing studies and the variety of anti-collision devices and installation intensities tested so far. First, summary statistics (e.g. means and associated variances) and/or sample sizes were often difficult to extract from studies and, in some few occasions, not reported at all, which led to the exclusion of the studies from the weighted meta-analysis. Second, as mentioned above, candidate explanatory variables were also often poorly reported, which limited the number of moderators included in the analysis and our ability to assess (or control) the effect of potential confounding factors, such as power line configuration and wire-marking intensity. Lastly, the variety of devices developed and tested in the studies and, consequently, the limited number of trials available for each type, forced a simplification of the moderator levels of the Type of device. For instance, the group named “Flappers” includes a wide variety of devices, whose particularities (e.g. shape, size, colour and luminescent properties) can affect the way birds perceived them. We had, however, to gather them in a single category, to guarantee that a minimum number of trials was available per moderator level.

The variety of wire-marking devices available, wire-marking intensities used and ecological circumstances in which the experiments were carried out, necessarily inflates the heterogeneity present in the dataset and limits the moderator analyses (Hempel et al., 2013). Nonetheless, there are other sources of between-study heterogeneity that are not related to true diversity among study outcomes, but to within-study methodological biases (Higgins et al., 2009). In our meta-analysis, the presence of such biases is evidenced by the existence of study trials in which the number of bird collisions with wire-marked power lines increased, compared to controls ( $\ln R > 0$ ; Fig. 1). We cannot discard the possibility that self-illuminated markers (e.g. with LEDs) or those that glow in the dark (with luminescent properties) may attract birds to the power line, but so far there is no published evidence that it might occur. Moreover, in our meta-analysis, none of the trials that obtained negative results was testing the effectiveness of luminescent (or illuminated) devices. This result is, therefore, potentially explained by within-study limitations,

namely:

- *Stochastic nature of bird collision with power lines and biases in carcass detection* – With some exceptions (e.g. Murphy et al., 2016b), the occurrence of a bird collision with an infrastructure followed by its detection (by observers) is, generally, regarded as a stochastic event (Korner-Nievergelt et al., 2013, 2011). Bird collisions may be highly concentrated in time and/or space, e.g. due to habitat features, intensive migration episodes, and adverse weather conditions or other stochastic events (Bernardino et al., 2018). Moreover, no or few carcasses may be found either because few animals were actually killed, or because they were missed in the carcass detection process due to crippling bias, limited survey coverage, carcass removal (by scavengers or decay) and searcher efficiency (Bernardino et al., 2013; Korner-Nievergelt et al., 2015), which increases the uncertainty in the mortality estimates both for wire-marked sections and controls.
- *Study design characteristics* – BACI designs encompass considerably less risks of violating the underlying assumptions than CI or BA designs, thus have higher power to detect true treatment effects, in particular if paired control-impact designs are adopted (i.e., with spatial alternation between wire-marked and control sections) (e.g. Yee, 2008). In practice, their implementation is often limited by the fact that mitigation measures are, for precautionary reasons, usually applied (1) during the project construction phase (e.g. European Commission, 2018; SNH, 2016), making it impossible to collect mortality data before the wire-marking treatment; and/or (2) in power line sections foreseen to be more sensitive for birds, which limits the selection of (true) control sections (e.g. Rytwinski et al., 2016; SNH, 2016). Therefore, sub-optimal study designs, like CI trials or BACI trials without paired control-impact design, are often adopted. In our meta-analysis, 6 of the 7 study trials which estimated implausible negative effects on bird collision rates ( $\ln R > 0$ ) were CI trials.
- *Limitations of methods used to correct observed mortality rates* – In sub-optimal study designs, observed mortality rates in wire-marked sections and controls should ideally be adjusted by the corresponding bird crossing rates and/or bias correction factors for imperfect carcass detection (e.g. due to carcass removal and searcher efficiency), to control for potential temporal-spatial differences in bird mortality rates - not related to wire-marking treatment. Unfortunately, bird surveys to determine flight crossing rates, as well as carcass removal and searcher efficiency trials also encompass several methodological limitations (Bernardino et al., 2013; Murphy et al., 2016b; Smallwood et al., 2018; Urquhart et al., 2015), which can inflate the biases associated with the adjusted mortality rates and, consequently, the estimated effect size, especially if those methods are implemented with low sampling effort.

## 5. Conclusions and guidelines for future field studies

Wire-marking is responsible for a significant reduction in bird collisions with power lines (on average, by 50%), although its positive effect seems to be lower than the one reported in the meta-analysis performed by Barrientos et al. (2011). The drivers of wire-marking effectiveness are still not clear due to the high variability in study outcomes, although we found a weak evidence that devices with moving parts (flappers) tend to be more effective. More studies are needed to confirm this result and further investigate the effectiveness of the different types of flappers (e.g. Fireflies, suspended discs, crossed bands), and how it may vary depending on target species, wire-marking intensity, etc. It is important to note that, flappers are particularly exposed to wind action and seem to lose their functionality faster than static devices (Dashnyam et al., 2016), which compromises their long-term effectiveness and entails additional costs with device replacement (Lobemeier et al., 2015). Studies evaluating the cost-effectiveness

of the different types of devices available on the market (and/or currently being developed) are, therefore, also needed.

The statistical power of future meta-analyses depends mostly on the quality of data used to estimate effect sizes and variances in field studies (Hempel et al., 2013; Lajeunesse, 2013). This can be achieved namely through (1) the conduction of more well-designed experiments, and (2) the control of potential confounders of effect size differences between studies. Therefore, we strongly recommend the adoption of BACI approaches with fine spatial-scale alternation between wire-marked and control sections ('paired samples' approach), to guarantee their similarity in terms of habitats, bird communities and carcass detection probability, among other confounding factors. The adoption of such experimental design allows the assessment of wire-marking effectiveness solely based on observed mortality rates, without the need for additional bias corrections (e.g. bird crossing rates, searcher efficiency, carcass persistence rates); which would also be beneficial and appropriate for the assessment of the effectiveness of alternative strategies to increase the visibility of the wires, like the use of lasers and U.V light (Dwyer et al., 2019; KIUC, 2015). If only sub-optimal designs can be adopted (i.e., BA or CI design), the conduction of additional field experiments (namely carcass removal/detection trials, and surveys to determine bird-crossing rates and/or flight behaviour) is recommended, first, to account for variations in bird mortality arising from external factors not related to wire-marking (e.g. Savereno et al., 1996) and, second, to link mortality rates to bird behavioural responses, in terms of reaction distances and manoeuvres to avoid the power line (e.g. Dwyer et al., 2019). Improvements in the quality of field studies can also be achieved with increased sample sizes (per combination of moderators tested) and proper control of potential confounding variables, even if (for logistic/financial reasons) it implies a reduction in the number of different type of devices, wire-marking intensities, power line features, habitats, etc. tested in a single study. In other words, it is preferable to use the available resources to implement a focused experiment (e.g. focused on one habitat type and wire marking device) rather than using a multi-objective approach trying to address at the same time different habitats and types of devices, which will result in small samples sizes for each of the moderators.

The impact of each individual study can then be maximized through its inclusion in meta-analyses. For that, it is crucial a broad dissemination of the study findings, together with a comprehensive reporting of the methods and results, even if wire-marking had weak or no significant effect on reducing bird collisions (Gerstner et al., 2017). A greater sharing of study results is extremely important, not only because it minimizes the risk of publication bias in meta-analyses and increases their power to detect moderator effects, but also because it prevents redundancy among research studies.

All these recommendations and important caveats to bear in mind in their implementation are summarized in Table 1, as well as the underlying weaknesses of the existing field studies identified through the present systematic review. With this exercise, we sought to increase the quality of future studies and maximize their contribution for the overall knowledge about wire-marking effectiveness, by facilitating their inclusion in meta-analyses. Finally, we highlight the importance of transferring this new knowledge to energy companies, policy makers and other stakeholders, so that it can be incorporated into EIA practice and contribute to an effective mitigation of bird collisions with power lines.

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**Table 1**  
Summary of the main limitations of field studies and recommendations to maximize their individual power and improve the overall knowledge on wire-marking effectiveness. BACI – Before-After-Control-Impact, BA - Before-After; CI - Control-Impact.

Topic	Main limitations in existing studies	Recommendations for future research
Experimental design	<ul style="list-style-type: none"> <li>Adoption of sub-optimal experimental designs (e.g. BA or CI), due to restrictions on the collection of mortality data prior to wire-markers installation and/or selection of (true) controls.</li> <li>Increased biases in effect size estimates, due to limitations in the field methods used to determine the bias correction factors of bird mortality (e.g. bird crossing rates, removal and detection rates).</li> </ul>	<ul style="list-style-type: none"> <li>Perform dedicated studies to assess wire-marking effectiveness, in order to enable the adoption of a BACI design.</li> <li>Select a relatively fine spatial-scale alternation between marked (impact) and non-marked (control) sections ('paired samples' approach) to perform the mortality surveys. Each pair of control-impact sections should not be too far apart to ensure that their differences (in terms of habitat, bird communities, scavengers' community, carcass detection, etc.) are neglectable. This allows the evaluation of wire-marking effect solely based on observed mortality rates, without the need for additional corrections.</li> <li>If only sub-optimal designs can be adopted (i.e., BA or CI design), conduct additional field experiments (namely carcass removal/detection trials and surveys to determine bird-crossing rates) to account for variations in bird mortality arising from external factors not related to wire-marking. Ensure that robust sampling schemes are adopted in order to minimize the uncertainty associated with the estimation of those correction factors.</li> <li>Ideally, carcass searches should be performed by the same observer(s).</li> </ul>
Sampling effort	<ul style="list-style-type: none"> <li>Conduction of short-term studies, which fail to detect temporal changes (seasonal or inter-annual) in bird mortality rates.</li> <li>Adoption of low-effort carcass search protocols (in terms of search frequency and length of power line surveyed), which can lead to biased bird mortality estimates due to the stochasticity nature of bird collision events and limitations in carcass detection.</li> </ul>	<ul style="list-style-type: none"> <li>Guarantee that seasonal and between-year variations in bird mortality are properly surveyed, both in wire-marked and control sections. Each experiment should cover, at least, one year prior to wire-marking treatment plus 2-3 years post-treatment.</li> <li>Ensure that, within the study seasons, the survey effort is appropriate for the study-site and/or target species, in terms of the expected number of bird collisions and/or carcass detection probability. Whenever these are expected to be low, the survey effort (carcass search frequency and extension of power line surveyed) should be increased in order to guarantee reliable conclusions.</li> </ul>

Table 1 (Continued)

Topic	Main limitations in existing studies	Recommendations for future research
Confounding variables	<ul style="list-style-type: none"> <li>Mix of potential ecological and/or project-related confounders (e.g. mix of different types of devices or habitats) in a same experiment.</li> <li>Insufficient number of experiments per combination of moderators, which limits the statistical power of meta-analyses.</li> </ul>	<ul style="list-style-type: none"> <li>Avoid the mix of wire-marking treatments (combinations of different devices and/or wire-making intensities) in a same experiment, to prevent confounding effects and increase the survey effort (per treatment sections and controls).</li> <li>Test the effectiveness of a same wire-marking treatment (type of device and wire-marking intensity) in different ecological circumstances (e.g. habitat types, bird communities).</li> </ul>
Reporting	<ul style="list-style-type: none"> <li>Unclear and/or selective reporting of study details and results, which hampers the calculation of effect size statistics and/or extraction of covariates (moderators) required for meta-analyses.</li> <li>Reporting of effect size statistics only for trials which evidenced statistically significant effectiveness ('p-hacking'), despite the informative value of non-significant results.</li> </ul>	<ul style="list-style-type: none"> <li>Describe clearly the experimental design, study temporal/spatial coverage and survey methods used.</li> <li>Discriminate the survey effort (e.g. number of carcass searches and kms searched) for each <i>treatment</i> and <i>control</i> section, and/or <i>before-after</i> study periods.</li> <li>Provide complete information about study area (e.g. habitat, target bird species), power line features (voltage, dimensions, wire arrangement, etc.) and wire-making details (devices characteristics and wire-marking intensity).</li> <li>Report all study outcomes, regardless of statistical significance and direction of the effect.</li> <li>Present either raw bird mortality counts or summary effect size statistics, including mean mortality rates, associated variation measures and sample size.</li> <li>Report summary effect size statistics separately for each <i>treatment</i> and <i>control</i> section, and for each study period (i.e., <i>before</i> and <i>after</i> treatment).</li> </ul>
Dissemination and access to study findings	<ul style="list-style-type: none"> <li>Publication bias towards studies showing positive wire-marking effectiveness, or novel findings;</li> <li>Limited access to studies conducted internally by the energy companies or under EIA processes (i.e., studies which were not conducted primarily with a scientific purpose).</li> </ul>	<ul style="list-style-type: none"> <li>Promote study publication, ideally, in peer-review journals, even those with negative (or not significant) effects;</li> <li>Ensure access and dissemination of study results, by making grey literature reports openly available online;</li> <li>Carefully choose the title, abstract content and keywords, to maximize study retrieval in systematic literature searches (e.g. using Google Scholar).</li> </ul>

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### Appendix A. Supplementary data

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