ENERGY & NATURE | *Methodology Report*

Avian-Power Line Collision
Overview of Risk Factors & Effectiveness of Wire Markers

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Renewables Grid Initiative

Contents

Chapter 1
Background & Objectives

1.1 About the Authors

The Renewables Grid Initiative (RGI)[1] is a non-profit organisation based in Berlin, Germany. RGI works together with a unique collaboration of climate and environmental non-governmental organisations (NGOs) and transmission system operators (TSOs) from across Europe in an ‘energy transition ecosystem-of-actors’ to promote fair, transparent, sustainable grid development to enable the growth of renewables to achieve full decarbonisation in line with the Paris Agreement.

RGI is convinced that the development of the electricity grid must go hand-in-hand with nature protection and restoration, preventing avoidable risk to biodiversity and, where possible, restoring ecosystems around electricity infrastructure. This core pillar of our work is defined in the ‘European Grid Declaration: on Electricity Network Development and Nature Conservation in Europe’ (RGI, 2012). Our work in this area has traditionally focussed on such issues as bird protection around the transmission grid and the potential of integrated vegetation management (IVM) to restore ecosystems in grid corridors.

Since our inception in 2009, RGI’s work on the topic of bird protection around power lines has entailed best practice promotion[2], convention of multi-stakeholder collaborative dialogues, organisation of public events supporting knowledge exchange, drafting and dissemination of communication and advocacy materials, and contribution to publications (e.g. Kettel et al., 2019). The measures available to grid operators to reduce the risk of bird collisions with their infrastructure have been a focus topic throughout.

Given positive findings from field studies and broad scientific consensus on the potential of wire markers to reduce power line collision risk for avian species (e.g. Barrientos et al., 2011: 2012; Bernadino et al., 2018), RGI advocate for the use of wire markers as an effective tool for electricity grid operation which is compatible with biodiversity protection. Moreover, we recognise that the efficient implementation of wire markers should be guided by:

1) Collaboration between grid operators and expert ornithologists (e.g. from civil society organisations and academia).
2) Accurate data on bird presence around power line projects.
3) Shared understanding of the factors that influence collision risk and thus the effectiveness of wire markers.

In response to the latter, RGI decided to launch this initiative. Conversations with various stakeholders across our ‘ecosystem of actors’, including several European grid operators, have

[1] Renewables Grid Initiative
[2] RGI Best Practice Database

confirmed a widespread lack of clarity regarding the effectiveness of wire markers in reducing collision risk for birds, as well as the technologies and methodologies available. Stakeholders have repeatedly highlighted the lack of uniformity in approaches both between and even within Member States (MS), which is confounded by certain key guidelines and studies being unavailable or only accessible in languages other than English. This knowledge gap is an obstacle to most effective use of wire markers and cost-efficient way possible. With this Report and the related Brochure, we aim to bring all available research on the factors influencing bird collision with power lines and the effectiveness of wire marking. As such, our goal is to contribute to a shared understanding of the issue at hand and inform best practice moving forward.

For questions on this initiative, contact Liam Innis, Senior Manager – Energy Ecosystems at liam@renewables-grid.eu or the communication team at communication@renewables-grid.eu.

1.2 Context & Discussion

The global transition towards cleaner, renewable energy sources (RES) plays a critical role in mitigating climate change and, in turn, reducing the risks it poses to ecosystems and biodiversity. This shift will necessitate an unprecedented expansion of infrastructure, both to harness RES - mainly through wind and solar-PV generation technologies - as well as transmission and distribution grids to bring this renewably generated electricity to consumers. The International Energy Agency (IEA) estimates that, to reach national climate energy and climate goals, a total of 80 million kilometres (km) will need to be added or refurbished by 2040, equivalent to a doubling of the existing global grids of around 7 million km of transmission lines and 72 million km of distribution lines (IEA, 2020; 2023).

Much of this new infrastructure will be in remote, potentially wildlife rich areas, and thus, we must recognise and account for the potential of this infrastructure to bring adverse effects on wildlife and the natural environment. A delicate balance must be struck between the expansion of clean energy infrastructure and the preservation of the natural environment. This balancing of priorities is a shared global challenge in the ongoing battle against climate change and the goal to halt and reverse biodiversity loss (Nature Positive, 2023).

Interactions between avian species and power lines have been a topic of discussion in science, engineering and the conservation community for many years, in particular the potential risks for birds through collision, electrocution and disturbance[3]. This report focuses only on the issue of collision and the solutions available.

Collision with power lines occurs when a bird fails to perceive an overhead wire as an obstruction in the airspace upon approach, hits the cable and dies immediately or due to injury. Collision can occur with poorly sited overhead power line of any voltage level: distribution, transmission or indeed communications lines. Birds rarely collide with the support structures (pylons or poles) and not all power lines pose an equal risk level, as it is influenced by a complex

[3] See LIFE-SafeLines4Birds for more information on these issues and measures which can be taken to reduce their impact. (LIFE21-NAT-FR-LIFE-SAFELINES4BIRDS/101073826)

interplay of bird-specific, site-specific and power line-specific factors (see chapters 3 & 4). Thus, the issue is more pronounced when certain power line constellations are in sensitive areas, for particularly collision-prone bird species.

However, it is understood that collision on transmission lines mostly occurs with the thinner, uppermost 'ground wires',[4] which are used on power lines of over 110kV to prevent damage to the conductor cables in case of a lightning strike. In Bernadino and colleagues' study of the factors influencing collision risk, of a total 208 collisions from across five studies, 84% involved ground wires, and 16% involved conductors (Bernadino et al., 2018). Field observations suggest that this could be a result of birds reacting to avoid the larger-diameter energised wires (i.e., conductors) and, in swerving the danger, flying upwards and subsequently collide with less-visible ground wires (Murphy et al., 2009; Martin & Shaw, 2010). It should be noted that transmission structures are taller and have longer spans between structures which increases the risk of collision.

Accurately quantifying the global impact of collision on bird populations is challenging due to a lack of uniformity in monitoring methodologies, limitations in collision victim searches, and a lack of robust, quantitative studies which could be used to extrapolate the collision rate per km per year on a larger scale (Prinsen et al., 2011a). In terms of difficulties in precisely surveying collision victims, bias can lead to an underestimation of collision rates, including carcass removal by predators, limited search efficiency of searchers (influenced by experience), and limited survey coverage (ibid.; APLIC, 2012; Bernadino et al., 2019). On the other hand, as many studies focus on areas where the collision rate is expected to be high (for example, due to a higher presence of collision-prone species), extrapolation of data could lead to overestimations (Prinsen et al., 2011a). While these factors urge caution when trying to quantify the issue of global bird collisions with power lines, there should be no doubt regarding the severity of the issue. Several scientific studies document that collision is a leading and unsustainable cause of mortality for some species, particularly in areas with high bird concentrations or endangered species (Bevanger, 1994; Drewitt & Langston, 2008; Martin, 2011; Shaw et al., 2021). A well-known example is the bustard family, which – being relatively fast, heavy fliers with very limited vision straight ahead, as well as being highly threatened, are prone to fatal collisions with power lines to the point that some populations are directly threatened by power lines (Silva et al., 2022).

Thankfully, solutions to mitigate these risks exist. This report will focus on the use of wire markers (also known as bird flight diverters – BFDs) to mitigate the risk of bird collisions with power lines (see chapter 2 for a fuller discussion of the mitigation hierarchy and all methods available).

The most widespread measure employed by electricity grid operators to mitigate the risk of bird collisions with overhead power lines is to apply marking devices that increase power line visibility to flying birds (Barrientos et al. 2011, APLIC, 2012, Shaw et al., 2021). Over the years, many different models of marker have been developed, for example swinging or rotating plastic

[4] Ground wires are also referred to as 'earth wires', 'shield wires' or 'lightning wires.'

plates, hanging plastic strips, PVC spirals of various sizes, rotating flappers, spheres, ribbons, tapes, flags, fishing floats, aviation balls, crossed bands etc. (APLIC, 2012; NABU & RPS, 2021). Markers come in different sizes, colours, materials and function. They may be 'passive', i.e. immobile, or 'active', i.e. mobile. Importantly, the different models available vary in their materials, installation method and general technical specifications. For example, many wire markers are intended for the ground wire, while some may be applied to the current-carrying conductor wires.[5] Furthermore, the cost and logistics involved in installing different types of wire markers vary widely and are important considerations for grid operators deciding which model to deploy (see chapter 6 for more information).

Despite the plethora of available marker models and use cases, surprisingly little reliable research is available on their effectiveness in reducing collision incidence. Historically, practical difficulties, lack of standardised monitoring procedures in the field, and the costs involved have precluded systematic study to gain a clear picture of the effectiveness of available wire marking technologies. A complex range of factors influences collision risk, and the effectiveness of wire markers in reducing that risk is similarly dependent on various elements. These include the bird species present, geographic location, power line configuration, the type of marker used, and how and where the markers are installed within the infrastructure (Bernardino et al. 2018).

Furthermore, where studies have been carried out, a lack of standardisation in study design and methodology impedes a linear comparison of results. Indeed, results are often found within grey literature documents (such as environmental impact assessment reports, technical monitoring reports, academic theses, and publications by civil society organisations), which can be scattered, available in various languages, difficult to access, and their methodology unclear (for a full discussion of study limitations, see Bernadino et al., 2018; 2019).

Despite this, in recent years, attempts have been made to systematically assess the effectiveness of different methods of wire marking, and generally confirm the overall ability of wire markers to *reduce* but not *eliminate* the risk of collision by making power lines more visible to approaching birds. A first-of-its-kind global meta-study carried out by Barrientos et al. (2011) demonstrated that wire marking had an overall positive impact on reducing the number of collisions with power lines by 55-94% (average 78%). A further meta-study in 2019 by Bernadino et al. found a lower average effectiveness rate of 56% (Bernardino et al. 2019).

It is therefore likely a both impossible and unrewarding task to seek universally valid conclusions on which is the 'best wire marker' by drawing direct comparisons between effectiveness scores by available research. Instead, when the research is assessed holistically, it becomes possible to define best practices for future projects with a view to further increase the effectiveness of anti-collision measures. Practitioners can benefit from such an overview to draw upon existing research and work with experts in the field to better review their own bespoke situation. In this way, we can move towards rolling out best practice bird protection measures in the field.

[5]Some concerns regarding the use of wire markers – particularly those which are mobile - on phase conductors include concerns regarding noise emissions, radio interference, and corona discharges (Hurst, 2004). See chapter 6 for more information on different markers.

1.3 Purpose & Audience

The primary objective of this work is to raise awareness among electricity grid operators, conservationists, and the public about effective strategies for mitigating avian collisions on overhead utility lines. It compiles and presents up-to-date international research on the effectiveness of wire markers in reducing bird collisions with power lines and the factors that enhance successful implementation. Furthermore, based on research, it seeks to offer readers an accessible understanding of various factors that influence collision with power lines, such as bird physiology and behaviour, geography, climate and technical aspects of the grid.

It is important to note, however, that this work does not seek to directly advise grid operators on which wire markers are the most appropriate to use in their context. These decisions should be taken on a case-by-case basis and should evaluate the several contextual factors which play a role. For more details on the technical specifications of the BFDs available on the market, we recommend contacting the manufacturers/distributors of the products. Furthermore, the goal of this report is not to 'rank' the bird markers on account of their effectiveness.

The primary audience for the brochure comprises electricity transmission and distribution system operators both within and outside the European Union (EU). It is designed to be a valuable resource for those responsible for regulating and implementing bird protection measures around power lines. Additionally, it serves as a reference for all stakeholders closely involved in bird conservation efforts, such as environmental organisations, solution providers and civil society.

1.4 Scope

This initiative consists of 2 constituent parts:

1) **Brochure**:
The brochure is designed to give an abridged, user-friendly overview on the topic and available research. This includes both information on the susceptibility of birds to collision with power lines and the factors which influence this, as well as some research into the effectiveness of wire markers in reducing mortality. It is important to mention that the size of this brochure limited the level of detail of the information it could contain. To ensure scientific rigour, we established standards for the research studies included, which limited the number of wire markers featured in the brochure (see chapter 1.5. 'Methodology'). These factors necessitated the creation of an accompanying methodology report.

Readers will note that the effectiveness table on the final page of the brochure only summarises four types of wire markers. This may seem surprising, given the multitude of products on the market. The reason for this is that these were the only wire markers for which a minimum threshold of scientific studies could be found, whose methodology allows for a fair discussion of these products alongside one another (see 1.5. 'Methodology'). An overview of the other studies considered within the scope of this work, some of which pertain to other wire markers on the market, is provided in Chapter 6 of this accompanying report.

2) **Methodology Report**

The Methodology Report provides a more comprehensive overview of the current state of research regarding the susceptibility of birds to collision (chapter 2), knowledge on the factors influencing this risk related to the birds (chapter 3), as well as external factors pertaining to the grid itself and site-specific factors conditions (chapter 4). The annex report also draws upon research to discuss what could be considered as 'basic principles for effective wire markers' (chapter 5). Next, the report introduces some of the wire markers available on the market, beginning with those presented on the brochure (chapter 6). Chapter 8 provides a full bibliography of sources. In the Study Summary Table, readers can find the results of our research overview of studies which considered the effectiveness of wire markers. Annex I summarises a total of 6 documents produced in the German context (and until now only available in German), which we consider to be useful to readers. Annex II is a translated version of a similarity index created as part of the study, which can be used to evaluate the susceptibility of 'comparison species' for which no research on collision risk susceptibility is available.

1.5 Methodology

Upon carrying out our literature review of available research into the effectiveness of wire markers, we faced considerable variation in the methodologies of field studies and the level of detail provided to describe the methodological process. This includes, for example, variations in the extent of the monitoring process, differences in sample size and period, and species involved. Furthermore, while some studies were subject to a process of peer-review and published in academic journals, others were only available online, for example on the websites of grid operators or environmental associations. Moreover, the studies we encountered had different data gathering processes, either *Before-After* (BA), *Control-Impact* (CI) or *Before-After-Control-Impact* (BACI). The BACI design is generally considered to be a more robust methodology as it accounts for differences between treatment and control groups, which – if not accounted for – can affect the reliability of conclusions (Bernadino et al., 2019; Christie et al., 2019). In the case at hand, such spatio-temporal variations could include differences in mortality rates between survey areas caused by factors other than wire marking, such as differences in bird abundance or carcass removal rates by scavengers (Bernadino et al., 2019).

Liesenjohann et al (2019) suggest a weighting scale which, by accounting for differences in methodologies and scientific rigour, allows for comparisons to be made between different studies. However, since our work was not designed as a scientific study, nor a systematic meta-study of existing research, we considered such an approach to be beyond the scope of our activity. Instead, we discussed with expert reviewers – including the authors of the Bernadino et al. (2019) study – to decide on another approach which would provide a scientifically valid basis for describing different studies alongside one another without entering complex calculations of study weightings. This approach followed the following steps:

- We refrained from calculating novel averages between different studies into marker effectiveness and instead clearly present the effectiveness scores calculated from individual studies' data sets.

- The methodology of the studies into the effectiveness of the markers should always be described and clearly marked for readers' attention.
- The **Methodology Report** would include a Study Summary Table of all available studies seeking to quantify the effectiveness of wire markers, regardless of their methodology.
- The **Brochure** would include an overview of studies for which a minimum of four scientifically rigorous studies were available. Our definition of 'scientifically rigorous' followed the methodology of Bernadino et al. (2019).
- We prioritised BACI-designed studies which were able to provide an effectiveness score (%) in terms of the reduction in collision incidents after wire marker installation compared to the before and control periods.
- Noting that there were too few BACI studies available to facilitate an interesting collocation of marker research, we would also include in the **Brochure** BA / CI-design studies on the condition that they had been subject to a peer-review process and clearly presented their methodology.
- For some studies, the effectiveness scores cited in the narrative text of the 'Results' or 'Conclusion' section differs from the actual data provided. Where this was the case, we worked closely with an expert researcher to calculate the true effectiveness score according to actual collision reduces as per BACI methodology. These figures were corroborated with the study's authors.
- Studies which followed these methodologies but were unable to confidently provide an effectiveness score would not be included in the **Brochure,** and instead included in the Study Summary Table.
- Studies which combined the effectiveness of more than one marker were not included in the brochure overview, and instead described fully in the **Study Summary Table.**

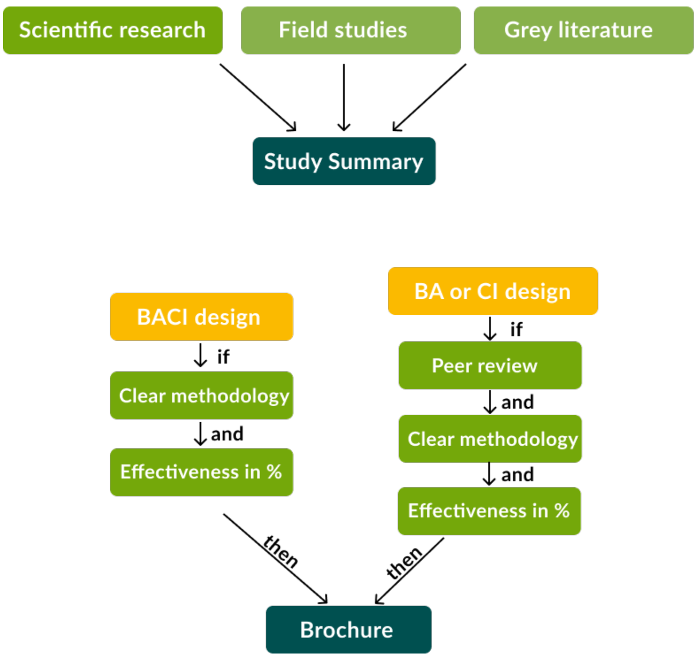

Figure 1. A visual representation of the methodology behind the Study Summary and Brochure. All studies are available in the Study Summary, the Brochure only features studies which fit certain scientific criteria.

For the purposes of reporting the results, wire marker studies were grouped into the following categories:

1) Dynamic small flapper marker - rotating (Indication element swings, rotates or flaps in presence of wind with max visible cross section < 250cmsq)
2) Dynamic large flapper marker - swinging (Indication element swings, rotates or flaps in presence of wind with max visible cross section > 250cmsq))
3) Static large spiral (double spiral)
4) Static small spiral (single spiral)

One marker in each of the groups 1-4 fulfilled the minimum standard of 4 BACI and peer-reviewed BA/CI effectiveness studies. The table in **Chapter 6.4** provides an overview of some technical details of these markers.

1.6 Call for more research

A major incentive to launch this initiative was the widespread perception within our network of a lack of overview, availability and uniformity in research studies on the topic – a position shared by several academics such as Bernadino et al. (2018; 2019) & D'Amico et al. (2018). Throughout our work, we identified several shortcomings in both the quality and quantity of research studies regarding the effectiveness of wire markers in reducing bird collisions with power lines.

Despite the large number of wire marker products in circulation, there are few robust, comparable studies into their effectiveness. For example, we frequently encountered studies whose data pools were too small to draw conclusions about effectiveness and several research papers did not provide clarity on the methodology to be fairly included. In this regard, we corroborate the guidelines established in Bernadino et al. (2019) for optimal future studies[6]. In particular, the researchers recommend the adoption of BACI study-design, increased sample sizes, and proper control of potential confounding variables, even if this implies a reduction in the number of different types of devices and other variables tested in a single study. A focused experiment (e.g. focused on one wire marking device and one habitat) is preferable to a multi-objective approach, which will result in small sample sizes. Where only BA or CI design is possible, the researchers recommend additional field experiments, such as carcass removal/detection trials, and surveys to determine bird-crossing rates and/or flight behaviour. These additional trials will ensure that external factors are accounted for, such as variations in bird mortality unrelated to wire marking and allow a link to be drawn between mortality rates and bird behavioural responses, in terms of reaction distances and manoeuvres to avoid power lines[7].

Regarding visibility of research results and methodology, our work highlighted the challenges

[6] Bernadino et al. (2019) provides a visual summary of the main limitations of field studies and recommendations to maximise their individual power and improve the overall knowledge on wire-marking effectiveness.
[7] Ibid. pg 7-8

of gathering a comprehensive overview of *all* available studies - indeed, several studies only came to our attention by experts involved in the review process. Many studies are only available on company websites and several studies lacked sufficient details on the methodology carried out. Therefore, we underline the importance of greater sharing of study results in academic journals, expert networks and general communication means. Broad dissemination provides a more direct contribution to scientific knowledge and industry awareness of best practices, but also minimises the risk of publication bias in meta-analyses and prevents redundancy among research studies. Finally, it is important that methods and results are reported in a clear and comprehensive way, even if wire marking was not found to have a significant effect on collision incidence (ibid.).

Finally, we reaffirm the vital importance of expertise and research from academia and civil society in informing best practices in the industry. RGI's years of experience confirm that such collaborations enable knowledge transfer, optimisation of resources, leveraging of scientific monitoring methodologies, co-creation of applied research to support management and decision making, the identification of commonalities and consensus and trust-building[8]. The generation of new research relies on stable financial resources from a variety of sources, including Europe's LIFE and Horizon programmes, national government grants, environment impact funds, and dedicated environmental or conservation funds at regional or local levels. Beyond this, we consider it important that regulatory authorities recognise the value of monitoring efforts for safe and nature-friendly construction and operation of the electricity grid and accordingly allow flexibility in budgeting processes for grid operators to conduct systematic monitoring efforts.

To summarise, our work has confirmed the need for:

1. More research into the effectiveness of wire markers in reducing bird collisions.
2. More standardisation in scientifically robust study design to ensure scientific validity and comparability of results.
3. Greater sharing and visibility of the research results.
4. More collaboration between key stakeholders.
5. Sustainable funding sources to facilitate more research.

1.7 Acknowledgements

In producing this work, several experts from ornithology, research, grid operators, planning offices, public authorities and conservation organisations were consulted. Their input was invaluable refining the scope of our work and in ensuring scientific validity and technical accuracy. We express gratitude to:

- Brian McGowan – Founder, Scientias Energy
- Joana Bernadino – PhD Researcher, BIOPOLIS/CIBIO
- Ricardo Martins – PhD Researcher, BIOPOLIS/CIBIO

[8] For more information and case studies of successful collaborations, see the document 'Collaborative Partnerships: For a resilient, bird-friendly electricity grid' produced under the LIFE-SafeLines4Birds project.

- Prof. Graham Martin – Emeritus Professor, Avian Sensory Science, University of Birmingham
- Dirk Bernotat - Head of Division II 4.2 Assessment instruments for nature conservation and infrastructure projects, German Federal Agency for Nature Conservation
- Marek Gális – Scientific coordinator of LIFE projects, Raptor Protection Slovakia
- Christin Osadnik, Consultant for Nature Conservation, Amprion GmbH
- Lars Haarhoff, Engineer Special Tasks Overhead Lines, Amprion GmbH
- Olivia Geels – Environmental Expert, Elia Transmission Belgium
- Johan Mortier – Environmental Expert, Elia Transmission Belgium
- Nadja Kucher - Environmental Expert, 50Hertz Transmission GmbH
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- Tris Allinson – Senior Conservation Scientist, BirdLife International
- Larissa Biasotto – Science Officer, Birds and Energy, BirdLife International
- Dominique Verbelen - Scientific Officer for Birds and Amphibians, Natuurpunt
- Dr. Jessica Shaw – Ornithological Advisor, NatureScot
- Catherina Schlüter - Bird Conservation Officer, NABU e.V.
- Dr. Mimi Kessler – Director, Eurasian Bustard Alliance
- Brooke Bateman - Senior Director, Climate & Community Science, National Audubon Society

Furthermore, we referred extensively to a great deal of high-quality work released in recent years. We endeavoured throughout to be diligent in providing sources when referencing information in the text (see also Bibliography, Chapter 7), however we also sought to avoid simply reproducing the conclusions of others, where readers could just as well refer to the sources themselves. Therefore, we provide below a brief list of further sources for interested readers.

1.8 Further Reading

Publication	Summary	Link
Martin, Graham (2017). The sensory ecology of birds.	This first integrated synthesis of avian sensory ecology by British scientist, Graham Martin, explains the broad principles behind the sensory ecology of birds and presents insights into the reasons why birds are often victims of collisions with static	Book

	structures, including power lines. His work gives important insights into to the development of mitigation measures.	
Avian Power Line Interaction Committee (APLIC). (2012). Reducing Avian Collisions with Power Lines: The State of the Art in 2012.	The 2012 edition of this manual provides electric utilities, wildlife agencies, and other stakeholders with guidance for reducing bird collisions with power lines. Chapter 4 "Understanding Bird Collisions" discusses in detail the biological factors of influencing collision risks (as well as the environmental and engineering aspects, which are covered in chapter 3 of this annex report).	Report
Bernardino et al. (2018). Bird collisions with power lines: State of the art and priority areas for research	This study is a systematic review of literature available on bird collisions with power lines, including (i) an assessment of overall trends in scientific research; (ii) a review of knowledge on species-, site- and power line-specific factors known to contribute to increased collision risk; (iii) an evaluation of the existing mitigation measures, including wire marking and underground cabling). Researchers underline the scarcity of research on power line-specific factors, of studies in Asia, Africa and South America and the need for further BACI (Before-After-Control-Impact) approaches to compare effectiveness of different wire markers.	Paper
Bateman et al., (2023) Audubon's Birds and Transmission Report: Building the Grid Birds Need. National Audubon Society	This report outlines how to ensure power infrastructure is built with birds in mind. It includes the latest scientific research and provides a roadmap for supporting an equitable, bird-friendly, and environmentally sound transmission buildout. The report includes a detailed topical overview and a variety of informative discussions on topics such as ornithological insights, policy and planning. Table 1 (page 15) was the original inspiration behind the 'Which birds are mainly susceptible to collision' table on page 2 of our brochure, which we expanded with some additional sources and an additional column (more details below). Annex documents provide valuable lists of sources & methodology information.	Report Annex documents

D'Amico et al. (2018). Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines.	This essay is a review scientific literature on both costs and benefits for avifauna coexisting with power lines for the context of landscape planning. The study highlights a generalised lack of studies focusing on these costs or benefits at a population level. The authors underline the need for collaborative dialogue among the scientific community, governments and electricity companies to produce a "win-win scenario in which both biodiversity conservation and infrastructure development are integrated in a common strategy."	Paper
Dwyer, J., Harness, E., Martín Martín, J. (2022). Chapter 4: Collision. Wildlife and power lines. Guidelines for preventing and mitigating wildlife mortality associated with electricity distribution networks. IUCN. pp.60-83.	This manual provides a technical guide for use by all stakeholders, including project developers and governments. It includes recommendations and standard good practices for avoiding the adverse effects of new power lines and managing risks early in the process, to ensure that infrastructure expansion takes account of biodiversity in the spatial planning and early project implementation phases, when they will be most effective. Chapter 4 covers the issue of collision, determining factors, anti-collision measures (and, crucially, effectiveness thereof), and recent advances in line marking and monitoring.	Manual
NABU & RPS (2021) Electrocutions & Collisions of Birds in EU Countries: The Negative Impact & Best Practices for Mitigation	An overview of previous efforts and up-to-date knowledge of electrocutions and collisions of birds across 27 EU member states (2021).	Study Press release
Prinsen et al. (2011a) Guidelines on how to avoid or mitigate impact of electricity power grids on migratory birds in the African-Eurasian region. Prinsen et al. (2011b); Review of the conflict between migratory birds and electricity power grids in the African-Eurasian region.	Guidelines and an accompanying International Review (Prinsen et al., 2011a) presenting available information on topic of bird mortality from power lines from the African-Eurasian region. These documents summarise the latest technical standards on electrocution mitigation and review and present guidelines to mitigate collision risk for birds.	Link 2011a Link 2011b

Chapter 2
Strategies to Mitigate Bird Collisions with Power Lines

In this chapter, we provide an overview of the issue of power line-related bird mortality, with a focus on collision and solution strategies to remove or mitigate this risk. Next, we outline why action on bird protection is a win-win situation for safe grid operation and biodiversity. Finally, we outline the state of legislation and guidance on this topic, as well as appropriate use of the mitigation hierarchy as a guide to developers in informing action.

2.1 Scale of the issue

In recent years, the number and rate of studies investigating the environmental impacts of power lines on biodiversity have increased rapidly, with most studies focussing on interactions between birds and power lines (see Figure 1, Biasotto & Kindel, 2017). The potential impacts of power lines on biodiversity throughout the different phases of development are several-fold and can produce neutral, negative or positive impacts. Biasotto & Kindel (2017) classify these impacts into several groupings, including for example:

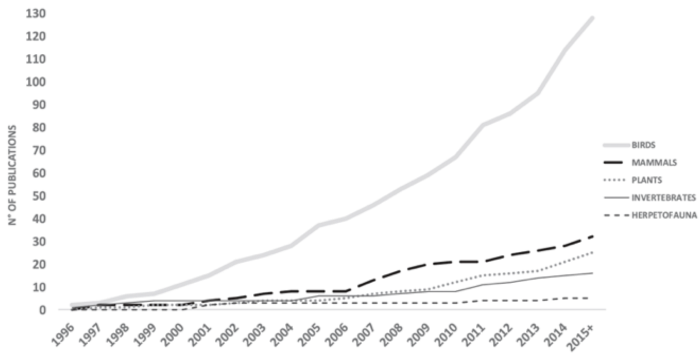

Figure 2. Cumulative number of scientific articles published on impacts of transmission lines per group (Biasotto & Kindel, 2017)

- Barrier effect: species perceive the line as a physical barrier (incl. collisions) or modify behaviour in response to a power line, incl. due to necessary vegetation management (D'Amico et al., 2018).
- Line as a resource: species use the line as a resource e.g. for perching, nesting, roosting and scavenging.
- Habitat conversion: Increase in available habitat of in abundance of individuals or colonisation by new species.
- Corridor effect: Individual movement along the corridor created by the right of way, incl. movements between habitats or for dispersal
- Others: Fragmentation, edge effect, electromagnetic field, habitat loss, fire risk, noise effect (see ibid.)

The issue of avian collision with power lines fits under the category of the 'barrier effect' (ibid.; Coleman et al., 2012). Collision is generally restricted to birds and other flying species which fail to see the power lines on approach, collide and often die from the impact or soon after from their injuries. Given the ubiquity of power lines across the globe, collision is likely the most widespread interaction of birds with power lines (Bernadino et al., 2018). Indeed, Biasotto & Kindel's global review of 206 academic articles and 19 environmental impact assessments (EIAs) into the impacts of the installation and operation of transmission lines on biodiversity found that 28% of all studies focussed on bird collisions.

On the other hand, mortality from electrocution risk falls under another category of biodiversity-power line interaction, namely 'line as a resource'. This is particularly pronounced in birds, which use the line to perch and forage (especially in otherwise flat landscapes, where raised structures are scarce), or indeed to nest and roost. Research and field observations confirm that power lines can, in this way, bring benefits for some species at the individual, population and community levels (Morelli et al., 2014). However, proximity with pylons can result in electrocution, usually on medium- and low-voltage pylons, where components are closer together than on transmission pylons. Electrocution occurs when an animal simultaneously touches a current-carrying (charged) component and a grounded component (e.g. power pole), or two charged components. This can lead to a short-circuit and is a known cause of failures in power transmission, which brings logistical and economic implications for grid operators and society (Prinsen et al., 2011). Furthermore, electrocution brings the risk of fire ignition as burning carcasses fall to the ground and ignite a bush or wildfire (see for example SCE, 2019).[9]

On a global scale, accurate quantification of the scale of mortality around power lines is confounded by such factors as a lack of solid, representative studies; bias (towards underestimations) in surveys of collision victims; and vast differences in the results gathered by studies (for a full discussion, see Prinsen et al., 2011a, section 3.3.2.). Where figures are available on estimate annual numbers of collision victims, these should be treated as rough estimates and treated with care.

Thus, to understand the scale of the problem, it is more sensible to consider cases where collision with power lines is documented to be a majority mortality risk for birds. Indeed, there are currently several known occurrences of particularly problematic power line constellations in areas with high bird concentrations and of endangered species whose population viability is directly threatened by power lines. A well-known example is the bustard family, which – being relatively fast, heavy fliers, with very limited vision straight ahead, as well as being highly threatened, are prone to fatal collisions with powerlines to the point that some populations are directly threatened by power lines (Silva et al., 2022; Shaw et al., 2021). For example, 30% of the global population of Denham's bustards *(Neotis denhami)* are killed by collisions every year and mortality rate of Ludwig's bustard *(Neotis ludwigii)* due to collision with power lines is understood to pose a real threat to the survival rate of this species (Jenkins et al., 2010; Martin, 2017). Furthermore, a study has shown that 12% of globally vulnerable Blue cranes *(Anthropoides paradiseus)* die each year as a result of collisions with power lines (Shaw, 2009). In several European countries, a high proportion of collision victims involve endangered species of Appendix I of the Birds Directive,[10] including European Spoonbill *(Platalea leucorodia)* and Black-tailed Godwit *(Limosa limosa)* in the Netherlands, and species of bustards and eagle in Spain and Portugal (Prinsen et al., 2011a).

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[9] Wildfire Mitigation Plan of Californian utility company, Southern California Edison, to proactively address and mitigate threat of grid-associated ignitions leading to wildfires. This came in response to a California Senate Bill 901 enacted in 2018 which required all utilities to prepare, submit and implement annual wildfire mitigation plans.
[10] Directive 2009/147/EC of the European Parliament and of the Council on the conservation of wild birds).

2.2 Collision Prevention: A 'Win-Win' Situation

For grid operators, the motivations to prevent collisions around their infrastructures stretches beyond biodiversity protection, yet ambition must be balanced with resources and budget considerations, as well as the overriding need to build grid infrastructure quickly to facilitate the energy transition. In this section, we will sketch out why it is a 'win-win' situation for grid operators to take all reasonable steps to tackle the issue of bird collision with their infrastructure[11].

Security of supply
Collision-related outages are less frequent than electrocution-related outage (see 2.1), however, some case studies demonstrate that the force of a bird flying into one phase conductor can connect phase conductors and cause outages. This issue is most common at lower voltages where the distances between parallel phase conductors are relatively short. For example, on the morning of 25th December 2023, a bird strike with a distribution line near Limerick, Ireland, caused an outage affecting 4,400 people[12]. Similarly, under the LIFE Danube Free Sky project, video footage taken in heavy rain and strong wind conditions captured 2 swans colliding with a 22kV line in Slovakia, causing a flashover[13].

Fire risk prevention
Furthermore, as with electrocution, the risk of fire ignition by sparks caused by collision is a further important factor in the need to reduce collision risk, especially in areas with elevated wildfire risk. The need for action to prevent wildfires is generally high on the agenda of grid operators and indeed several grid operators in RGI's network run projects to examine both how they can minimise the risk of their power lines igniting fires, but also how the presence of their infrastructure in the landscape can contribute to early warning systems for rural wildfires[14].

Public support
Surveys show that public awareness about biodiversity and concern for the protection of nature are higher than ever before (OFB, 2023; EEA, 2021; WWF, 2021). Within organised civil society, biodiversity conservation concerns are commonly cited reasons for opposition campaigns against power line projects, with the issue of bird mortality perhaps most present in the public discourse. Experiences show that, while press coverage of collision incidents frames grid operators in an overwhelmingly negative way, stories about action taken by grid operators to reduce impacts of their infrastructure on birds are framed in a positive, constructive way. Positive public reception of bird protection initiatives is multiplied again when grid operators show a readiness to collaborate with civil society (e.g. through NGOs or citizen science initiatives) and academia to protect biodiversity. Two good examples of this are RGI's 'Bird Portal' in Germany, a collaboration between NABU (BirdLife Germany) and seven German grid operators, and a collaboration between Belgian TSO, Elia, and two NGOs, Natuurpunt and Natagora (see box in 2.4)[15]. Importantly, transparent partnership with civil

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[11] Policy related aspects and contribution to biodiversity protection targets are discussed in section 2.3.
[12] Article in 'LimerickLive' newspaper
[13] LIFE Danube Free Sky (LIFE19 NAT/SK/001023)
[14] Learn more in RGI's Energy & Nature webinar, 'Fire Watch: How can the grid help prevent wildfires?'
[15] Find here two introductory videos to the Bird Portal & Belgian collaboration

society also provides important opportunities to clearly explain to the general public the need for grid infrastructure in bringing about the energy transition and the potential for nature-friendly development[16], in turn dispelling misinformation and potential further opposition.

2.3 Legislation & Guidance

An extensive overview of international policy initiatives and available guidelines to tackle the issue of bird mortality around power lines can be found in Prinsen et al., (2011a; b). Specifically, in the EU context, Raptor Protection Slovakia (RPS)[17] have drafted an overview of the legislation and the status quo of implementation in all EU Member States (NABU & RPS, 2021).

In general, regulations and actions specifically addressing the impacts of power lines on birds have been absent from the wealth of national and international legislation providing for the protection of birds (Prinsen et al.; 2011a). Historically, this has led to a situation where, in many countries, an inflexible regulatory framework or insufficient budget resources have prevented grid operators are from applying state-of-the-art measures to prevent mortality from collision at scale (ibid., 2011b).

Three international treaties have included reference to the issue of collision and electrocution, namely:

- 1979 - Convention on the Conservation of Migratory Species of Wild Animals (known as the 'Bonn Convention').
- 1979 - Convention on the Conservation of European Wildlife and Natural Habitats (known as the 'Bern Convention').
- 1999 - African-Eurasian Waterbird Agreement (AEWA).

In the wake of these conventions, resolutions and guidance documents on reducing negative impacts of power lines on birds have been produced. For example, the Energy Task Force, set up under the Bonn Convention (CMS) provides a multi-stakeholder platform for reconciling renewable energy developments with migratory species conservation. Furthermore, the Infrastructure & Ecology Network Europe (IENE) promotes knowledge exchange and collaboration between ecologists, industry, and governments on the topic of linear infrastructure, including power lines. Still, where effective action has been taken, it rather focusses on the topic of electrocution than collision.

The Birds and Habitats Directives[18] are the cornerstones of the EU's biodiversity strategy and provide a common legislative framework for Member States to conserve Europe's most endangered and valuable species and habitats, irrespective of political or administrative boundaries (NABU & RPS, 2021). Certain Member States have gone on to enshrine the stipulations of the Birds Directive into national law – however readers will note that the focus lies mainly on electrocution. For example:

[16] For more information and case studies of successful collaborations, see the document 'Collaborative Partnerships: For a resilient, bird-friendly electricity grid' produced under the LIFE-SafeLines4Birds project.
[17] This review was commissioned by the Nature and Biodiversity Conservation Union (NABU – BirdLife Germany)
[18] Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora.

- Under Germany's 'Federal Nature Conservation Act' (*BNatSchG*), paragraph §41 requires all newly erected power poles of medium-voltage power lines must be constructed in a way which prevents electrocution. Where existing poles are proven to pose an electrocution risk, these must be retrofitted.
- Spain's 'Royal Decree 1432/2008' specifies poles and distances between insulators which must be used to prevent bird electrocution. Furthermore, the law defines technical specifications for the deployment of some wire markers, including the distances between markers (every 10 metres on solitary ground wires or every 20 metres on alternative parallel ground wires/conductors). Importantly, the law leaves the decision of whether to install wire markers to the regional authorities and also did not provide budget to implement collision measures.

Generally, there is little guidance available to grid operators on which of the available models of wire markers grid operators are to be used, and the choice is left up to the company. However, in Germany, two key guidance documents have been released by the coalition of State Bird Protection Authorities (LAG VSW, 2012) and Grid Technology and Grid Operation Forum (FNN) of the German Association for Electrical, Electronic & Information Technologies (FNN/VDE, 2014) which explicitly favour the use of black and white markers which omit a 'blink effect' (see Annex I for extended insights from relevant German studies).

In terms of project planning, Strategic Environmental Assessments (SEAs) and Environmental Impact Assessments (EIAs) are widespread and commonly implemented in many countries around the globe (Prinsen et al., 2011a; b). These are key processes in terms of identifying and responding to the potential impacts of power line projects on birds at different phases of planning scoping, planning, and deployment. SEAs, which are carried out before the individual project stage, enable the proactive identification of high-risk areas to inform power line routing decisions. The more granular EIA process comes later in the planning process of individual power lines and allows for the assessment of potential impacts at the project level, thus providing a key tool for identifying and minimising risk for birds.

At the time of writing, several major new policy initiatives at global and European level aim to advance the protection and restoration of biodiversity. At international level, under the Montréal-Kunming Global Biodiversity Framework (GBF) signatories commit to "take urgent action to halt and reverse biodiversity loss" (UNEP, 2022). The current decade 2021-2030 is known as the 'UN Decade on Ecosystem Restoration' which inherently includes the restoration of habitats for birds. Several grid operators have responded with ambitious initiatives to amplify their efforts to protect biodiversity (including birds) and restore ecosystems around their infrastructure. Good examples here include:

- Elia Group's[19] 'Act Now' sustainability strategy includes commitments to retrofit 100% of high-voltage lines in critical bird areas with wire markers by 2030 (from 75% in 2023).
- Redeia Group (incl. Spanish TSO, Red Eléctrica) aim in their 2023 Sustainability Report to "achieve a positive impact on biodiversity and 'living in harmony with nature' in line

[19] Elia Group includes TSOs Elia (Belgium) and 50Hertz (in several 6 federal states in eastern Germany, incl. Berlin)

with the 2050 Vision of the United Nations Convention on Biological Diversity". This includes the retrofitting of 100% of critical spans with wire markers by 2025.
- European DSO network E.ON has started a partnership with the United Nations Environment Programme for the Decade on Ecosystem Restoration.

The EU's Nature Restoration Law, passed into law in July 2024, will require Member States to restore 20% of terrestrial and marine ecosystems by 2030. In this effort, it is likely that all parts of society, including operators of large pieces of infrastructure, will have a key role to play around their infrastructure. Furthermore, for businesses operating and trading in Europe, the Corporate Sustainability Reporting Directive (CSRD) will, for the first time, place sustainability reporting in Europe on equal footing with financial reporting. Under the category of standards, E4 'Biodiversity and Ecosystems', companies will have to transparently disclose impacts and interdependencies with nature and demonstrate mitigation measures to counteract negative impacts. This will include impacts on birds, as companies report on risk and the implementation of mitigation measures.

2.4 The Mitigation Hierarchy

The mitigation hierarchy is a useful tool in reactive management of environmental impacts and supports infrastructure developers towards limiting and counteracting potential negative impacts on biodiversity. Indeed, it is well-established within planning processes, for example EIAs. The Cross Sector Biodiversity Initiative defines the hierarchy as *"the sequence of actions to anticipate and avoid impacts on biodiversity and ecosystem services; and where avoidance is not possible, minimise; and, when impacts occur, rehabilitate or restore; and where significant residual impacts remain, offset."* (Ekstrom et al., 2015).

On the first page of our brochure, we provide an adapted version of the mitigation hierarchy with available measures at each phase appropriate to the issue of collision. Below we will give more detail on these suggested actions, as well as some best practice examples. Please note, these examples should not be taken as official guidance on mitigation measures and project developers should also follow the appropriate steps of the planning process, such as those stipulated by EIAs.

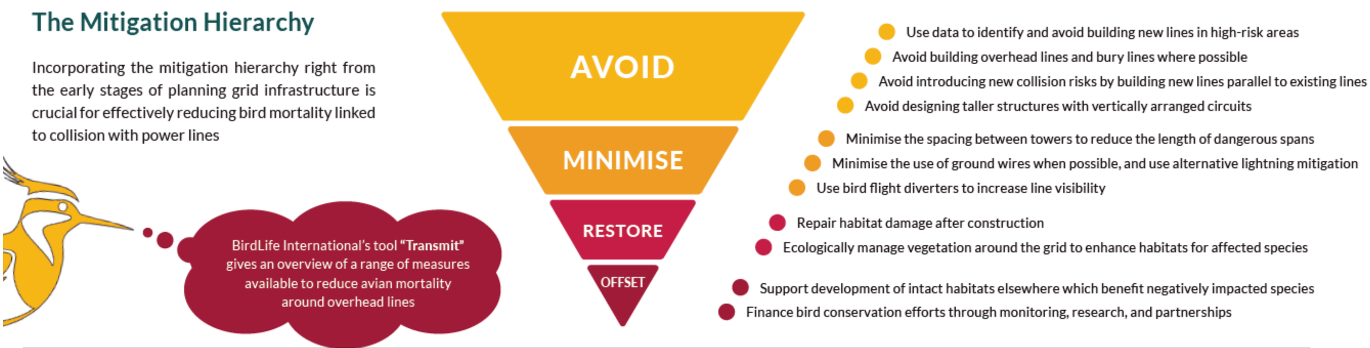


Figure 3: The above model from the Brochure will not always be practical, (i.e. ground wire removal) and is only offered as a guide. When an action is not possible to follow due to conflicting priorities, the emphasis of the design team should always shift to mitigation steps first, and if this mitigation is not possible, then to restoration, offset etc. Source: RGI

The sequential steps of the mitigation hierarchy are as follows:

1) Avoid: Avoidance is the most effective solution to remove the risk of significant impacts on wildlife from the outset. Careful, well-informed planning which avoids the problem of collision by avoiding high-risk areas entirely is always preferred over retrospective efforts to mitigate the issue. By taking steps to collate/gather data on bird presence (e.g. migration routes, sensitive areas), often in collaboration with scientists and/or civil society organisations, grid operators can ensure that new infrastructure avoids areas which could lead later to high levels of collision, or even to re-route existing power line corridors away from high-risk areas. It is worth mentioning that such participation opportunities also show an openness on behalf of the grid operator to consider and respond to the expertise of other actors, which can prevent public opposition at a later stage and contribute to a more positive public image. Costs for good planning can be high but should be considered compared to the cost effectiveness of mitigation over the entire project life cycle and factored against lengthy and uncertain alternatives like restoration or offsetting (BirdLife International, 2020 – Transmit).

Good examples of such collaborative, data-based planning abound, with the creation and use of 'risk maps' or 'sensitivity maps' standing out as a clear best practice in this regard. Specific best practices are featured in the boxes throughout this chapter.

AVISTEP – The Avian Sensitivity Mapping Tool for Energy Planning

Launched in 2020, BirdLife International has developed an online sensitivity mapping tool which uses the best available data and local experts to create robust maps to inform the planning of power lines and RES infrastructure away from bird-sensitive areas.

The tool has been implemented with some success in countries such as India, Thailand, Keyna and Egypt and is currently being expanded to other countries. Moving forward, it is intended that AVISTEP will be established as the global tool for assessing avian sensitivity in relation to energy infrastructure and therefore will underpin the next 10-20 years of the clean-energy transition. Read more in the RGI database here and find the tool here.

Wildlife Sensitivity Mapping Manual:
Practical Guidance for renewable energy planning in the EU

This guidance manual draws together the information needed to develop for effective wildlife sensitivity mapping approaches within the EU. This includes a comprehensive overview of relevant datasets, methodologies and GIS resources. It was drafted with renewable energy in mind, but the approaches are applicable to grid planning. The document comes from the European Commission and was drafted in collaboration with expert ornithologists. Find it here.

Burying power lines underground is a way to entirely remove collision risk and should be considered wherever technically possible. However, it must be noted that the undergrounding process is associated with much higher costs (for installation and maintenance), is not always technically feasible (especially for long stretches of high voltage power lines and those operating on alternating current). Moreover, it can be challenging to place cables underground in areas which, on account of geographical characteristics, pose a higher risk to birds, i.e. across water and mountainous terrain.

When additional capacity is required to transport more electricity, it is beneficial to consider upgrading existing power lines before building new ones. However, if new lines are required building them parallel to existing infrastructure can help minimise the overall space used by power lines, reducing the potential new conflict areas where collisions might occur.

Collaborative risk mapping to reduce collision in Belgium

In 2012, Belgian national TSO Elia launched a collaboration with two NGOs Natagora and Natuurpunt to create a risk map quantifying bird collision risk across Belgium. Using extensive research and volunteer efforts, they identified collision-sensitive bird species and developed species-specific risk maps, integrated into a comprehensive 'risk scoring system'. This pioneering mapping effort provides crucial data for Elia to plan new power lines and implement mitigation measures effectively. A pilot project in Oudenaarde demonstrated significant reduction in avian fatalities, from 70 to 2 individuals, after installing bird flight diverters informed by these maps. Regular updates support Elia's risk assessments and support the execution of their sustainability programme 'ActNow' in planning mitigation actions. Read more here.

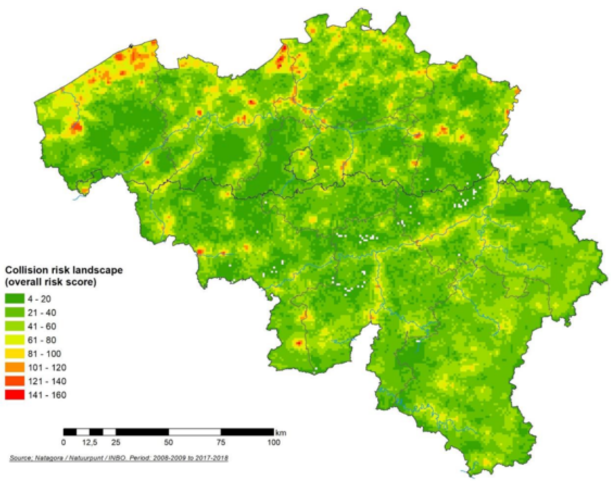


Figure 4. The final collision risk landscape for Belgium, showing a gradient of bird collision risk, should a power line be built in any location (Natagora, Natuurpunt, INBO, 2020).

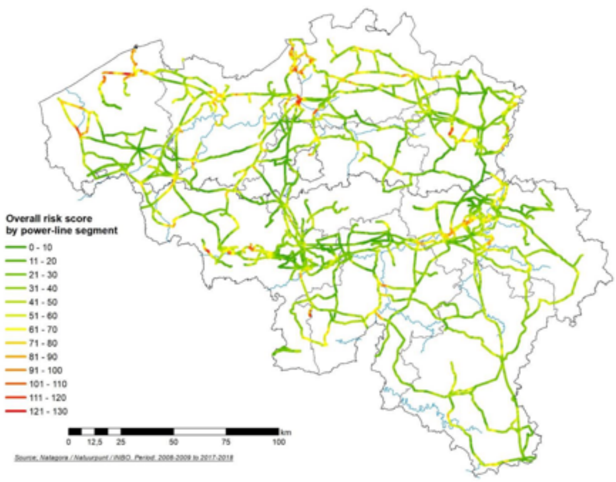


Figure 5. Map of current Elia grid of power lines (including sections owned by other parties but managed by Elia). Sections are colour-coded based on their collision risk scores (Natagora, Natuurpunt, INBO, 2020).

2) Minimise: Measures taken to minimise impacts are those which reduce the duration, intensity of extent of impacts which cannot be completely avoided. It is at this point of the hierarchy that wire markers become relevant – they will not fully remove the collision risk, but by making the lines more visible, they reduce it. Still, it can be difficult to know where to deploy wire markers to maximise the benefits in terms of collision risk reduction. It is therefore recommended for grid operators to work together with local experts, such as ornithologists and civil society organisations to inform the localisation of wire markers. Furthermore, as in the planning phase, a data-driven approach using risk/sensitivity maps can be extremely useful in prioritising the placement of wire markers.

Furthermore, in some countries it is common practice to 'bundle' current carrying wires to increase their visibility to approaching birds. This, however, does not address the low visibility of the ground wire.

Figure 6. A selection of wire markers used by grid operators to mitigate the risk of collision on their power lines (used with permission from Scientias Energy).

3) Restore: This step aims to improve on-site degraded ecosystems following exposure to impacts and may relate to the site baseline prior to impacts, or indeed to a reference site elsewhere in the ecosystem (Ekstrom et al., 2015). In the case of power lines, it could be argued that true restoration is not possible, namely because the line will continue to pose a risk if it is present - with restoration following removal of an old power line being a notable exception (BirdLife, 2020). However, habitat restoration in the area occupied by power lines can indeed take place following disturbance during the construction phase and continue into the operation phase. In this regard, a consideration of a grid operator's vegetation management techniques becomes relevant. Rather than clear cutting the area around power lines to prevent risk of a fire or outage from a tree touching a line, grid operators can instead selectively remove 'problematic' trees; promote slow, low-growing, native species; take steps to support the development of critical native ecosystems, etc. This approach is commonly referred to as Integrated Vegetation Management (IVM).[20]

Integrated Vegetation Management: Best Practices from across Europe

Historically, the prevailing logic of conventional vegetation management has been to eliminate risk of interference with power transmission through periodic, indiscriminate removal of all vegetation in a defined corridor around power lines, often at the expense of the environment and without the involvement of local stakeholders.

In contrast, Integrated Vegetation Management (IVM) takes a more holistic strategy by promoting the growth of low-impact vegetation ensures safe operation of energy infrastructure, while supporting habitats for biodiversity, connecting ecosystems at landscape scale, and creating socio-economic benefits for local stakeholders. For an overview of approaches taken by several grid operators from across the European continent, consult IVM's Best Practice Guide here.

However, habitat restoration in the immediate vicinity carries the risk of forming an 'ecological trap', in which birds are attracted to the area due to the habitat, but then suffer an increased mortality risk through collision or electrocution (Phipps et al., 2013). We thus recommend the restoration to be coupled with the use of measures from the previous step, such as wire markers.

4) Offset: This final step of the conventional mitigation hierarchy refers to actions which are applied to areas *not directly impacted* by the project but seek to compensate for impacts in the project area which could not be avoided. Offsetting may include the restoration of degraded habitat for affected species elsewhere, protection of areas or species under threat, or other measures that will help compensate for mortality risk caused by infrastructure. A common aim for offsets is to achieve 'no net loss' of biodiversity – which are required by some regulators and financial institutions – however the governance of biodiversity offsets is complex and there is extensive discussion around their effectiveness (see IUCN, 2014; Ermgassen et al., 2019), and therefore they should be considered a last resort if avoidance and minimisation fail (BirdLife, 2020). Still, for compensatory measures to remedy the potential harm they brought about by a development, they should target the bird species negatively affected by that project and be implemented within the biogeographical region concerned. Typically, the European Commission considers that "payments to individuals or towards special funds, regardless of whether or not these are ultimately allocated to nature conservation projects, are not suitable"[21] as compensatory measures.

Grid operators can also consider providing funds and resources to support research, monitoring and collaborations, and thus further scientific and practical understanding of the interactions

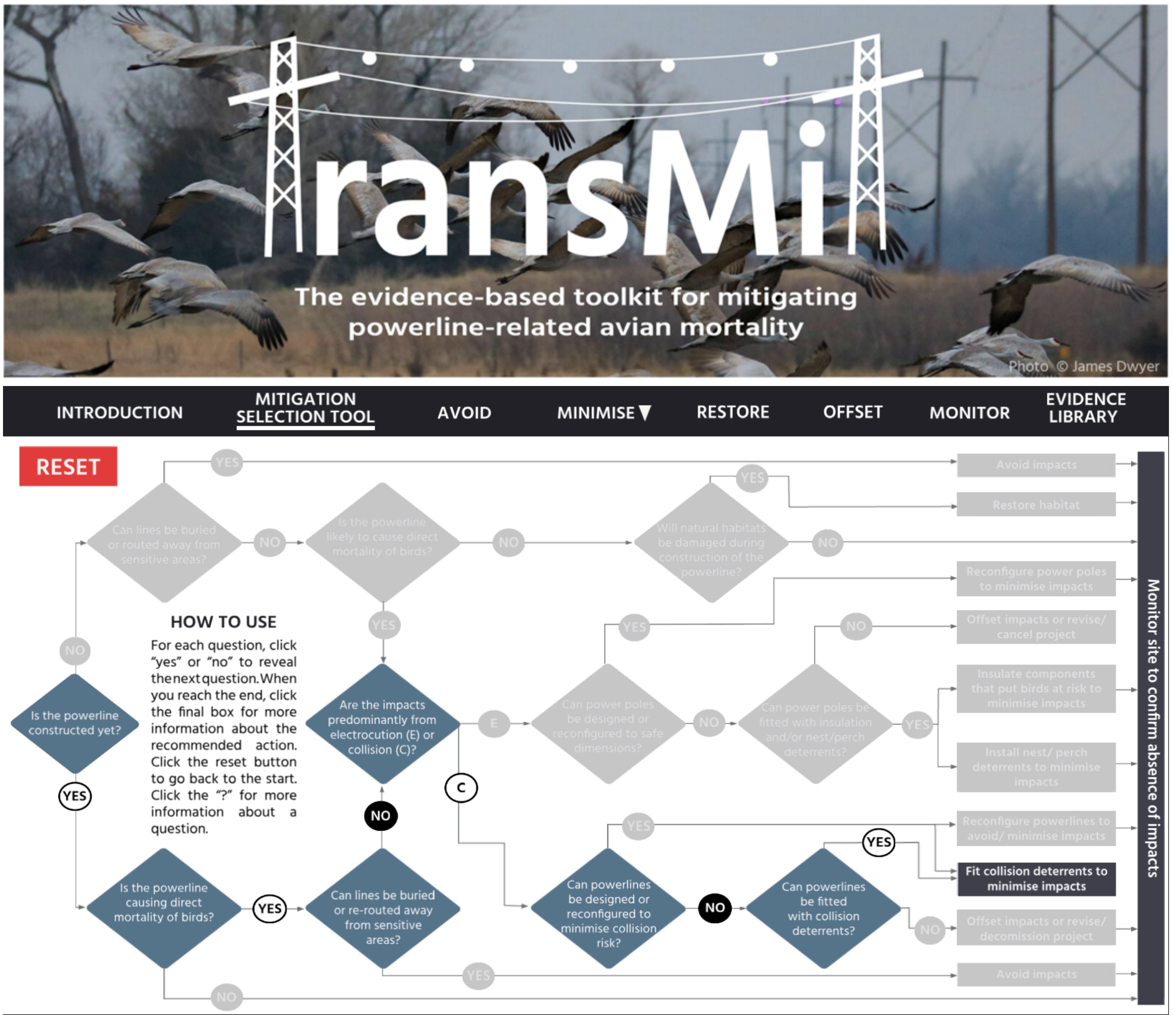
[20] For more information on IVM, visit our website and consult our IVM Best Practice Guide (RGI, 2024)

[21] European Commission (2019). Managing Natura 2000 sites — The provisions of Article 6 of the Habitats Directive 92/43/EEC (OJ C, C/33, 25.01.2019, p. 1, CELEX: link

between birds and power lines. Grid operators can consider supporting (collaborative) monitoring efforts and set aside resources to quantify occurrences of collisions with their infrastructure, especially at locations where wire markers have been fitted. As discussed in section 1.5., there is a general lack of high-quality studies into the effectiveness of wire markers, which must be remedied by more studies which follow a BACI methodology.

Transmit – The Evidence-based Toolkit for Mitigating Powerline related Avian Mortality

BirdLife International, working together with others in the context of the Energy Task Force of the Convention on Migratory Species (CMS), developed an evidence-based toolkit for mitigation powerline-related avian mortality, named 'Transmit'. This includes extensive guidance on measures to tackle both collision and electrocution, including a user-friendly 'Mitigation Selection Tool' in flow-chart style and an 'Evidence Library'. See images below.



Chapter 3

Which Bird Species are Most Susceptible to Collisions with Power Lines

The second page in the brochure presents a table including a range of bird groups whose members typically exhibit such collision risk-relevant characteristics. The content of this section, including the table format is inspired by the Audubon Society's 2023 "Birds and Transmission; Building the Grid Birds Need" (Bateman et al., 2023a), and has been adapted with other sources and the advice of expert ornithologists. In the right-hand column of the table, we present a selection of species which have been shown to be most at risk to collision according to research from (inter)national studies which combined collision-susceptibility with other factors such as data on reported collision events, potential population impact of collisions, and conservation status to create a 'Collision Sensitivity Index' (further detailed in section 3.3.)

The aim of this page is to give readers a rough impression of bird groups which may be a particular cause for concern around a power line project. However, the list is not exhaustive, and bird presence should be subject to further investigation and data cross-checking, for example as part of the EIA process.

Due to limited space in our brochure, we combined some bird groups with similar risk factors and featured only a select few representative species as examples. For the sake of comprehensiveness, this chapter of the methodology report we present the full list of birds and their bird factors related to collision susceptibility. Tables 1 & 2 separately present factors related to bird morphology and behaviour. We also provide an overview of research in order to provide readers with a more comprehensive understanding of bird-inherent factors which make some birds more susceptible to collision.

Birds' inherent sensitivity to collision with power lines results from a combination of their physical characteristics and the behaviour they exhibit. These can be separated into two broad classes of factors:

- Behavioural aspects, e.g. social tendencies, migration, feeding, roosting, flocking, hunting, circadian rhythm (Prinsen et al., 2011a; Bateman et al., 2023a).
- Morphological aspects - which in turn can be broken down into body shape; and sensory ecology, i.e. visual and perceptual aspects (Prinsen et al., 2011a; Martin et al., 2012; Bernadino et al., 2018).

Birds which exhibit a combination of these factors will be particularly susceptible to power line collisions. As an example, in his 2022 paper, "Vision-Based Design and Deployment Criteria for Power Line Bird Diverters", Graham Martin describes the Canada goose *(Branta canadensis)* as a worst-case species upon which to base power line diverter design and deployment. The Canada goose's high susceptibility to collisions is based on a range of factors discussed in the following pages, linked to its weight (body mass 4-5kg), high flight ground speed (61-68 km/h), low aerial manoeuvrability, low visual resolution and acuity, as well as its tendency to fly in groups and fly regularly between roost and feeding sites at dusk and dawn in poor visibility conditions (Martin, 2022).

Chapters 3.1. and 3.2. provide the research basis for the table on page 2 of the Brochure, 'Which birds are mainly susceptible to collision?'.

Bird groups with higher suscepti-bility to collision with power lines	Avian morphology factors		Avian behaviour factors				
	Wing size, weight, speed & manoeuvrability	Vision	Flocking / gregarious	Long distance migration	Nocturnal birds & night migration	Foraging / roosting trips	Aerial hunters
Pelicans, herons, egrets, bitterns, ibis, spoonbills	x	x	x	x	x	x	
Cranes, rails, gallinules	x	x	x	x	x	x	
Waterfowl (e.g. ducks, geese, swans)	x	x	x	x	x	x	
Waders, gulls, and storks	x	x	x	x	x		
Bustards	x	x	x	x		x	
Divers, grebes, and cormorants	x	x	x	x			
Eagles, hawks, harriers, vultures, and falcons	x	x		x		x	x
Owls		x		x	x		
Landfowl (e.g. grouse, pheasants)	x	x		x	x		
Passerines (incl. corvids)	x		x	x	x		

Figure 7: This table, taken from page 2 of the Brochure, depicts bird groups which are more susceptible to collision on account of morphological and behavioural factors. Tables XX and YY at the end of chapters 3.1 and 3.2 provide references from research which confirm the placement of the 'x's next to the respective bird group. This initiative was inspired by the work of the American conservation NGO, Audubon Society (Bateman et al., 2023a; b)

3.1 Avian Morphology Factors Influencing Collision Risk

Visual perception

In birds, the eyes are generally placed laterally (outwards-facing) in the skull, in contrast to humans, where the eyes face directly forward and can be used in tandem to view a single object - 'binocular vision') (Martin, 2011; 2017). Thus, while birds are indeed able to see straight ahead of them, the area of their visual fields with the highest resolution and colour discrimination capacities face to the sides. This is beneficial for tasks such as the detection of approaching predators, or the presence of members of the same species. On the other hand, birds' forward vision is important for near tasks, such as pecking, nest building and feeding chicks (ibid.; 2017).

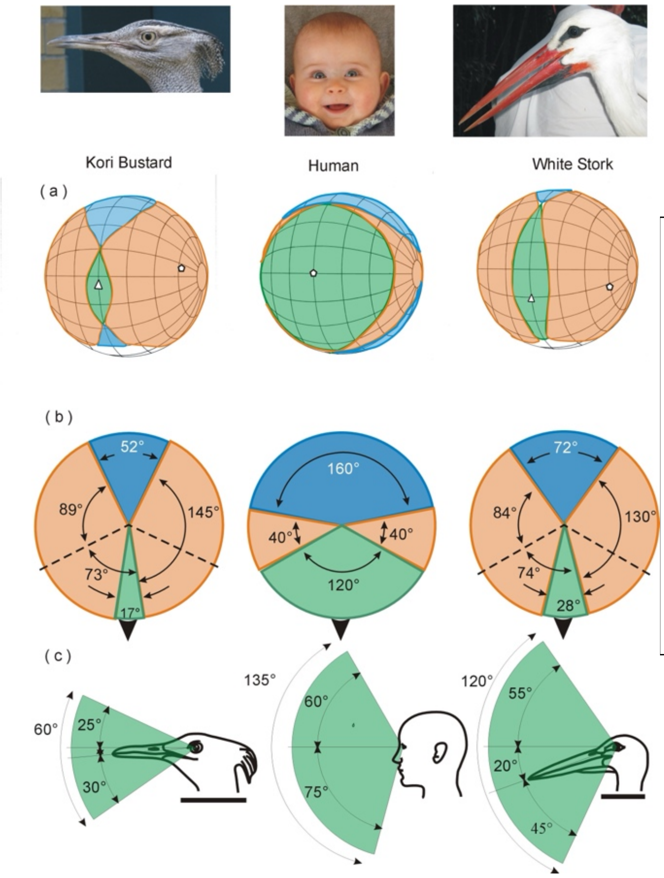


Figure 8. Variation in bird and human visual fields. How each eye's visual fields combine produces differences in the size of the binocular field (where the fields of the two eyes overlap: green), blind areas above and behind the head(blue), and the portion of space that is viewed by each eye alone (orange). Taken from Martin, 2017.

Figure 9. Rayner (1998) considered factors of wing loading and wing aspect ratio to separate bird groups into different classifications, including one group of "poor" fliers. Bevanger (1998) took this further to link "poor" fliers to a higher collision susceptibility.

The relevance of the eye placement in the skull is relevant for birds' susceptibility to collision with power lines, as it means that birds tend not to be looking straight ahead of them during flight and are thus less equipped to perceive obstacles in front (indeed, up until the erection of power lines and other human infrastructure, 'open sky' had typically been free of obstacles for birds). It follows those birds with particularly narrow binocular fields, such as bustards, storks and cranes, are more susceptible to collisions (D'Amico et al, 2018). Furthermore, the size and movement of the bill can further inhibit frontal vision (APLIC, 2012), and in some species, e.g. Eastern Hemisphere vultures *(Accipitridae)*, the presence of an eyebrow ridge to block out the sun's glare can create a blind area straight ahead. Another important factor is that some birds angle their heads downwards in flight (e.g. to look for food, water or members of the same species), which can result in a blind zone in the direction of flight (see *Figure 8*). Studies have shown this to be the case in a number of collision-prone species including Blue cranes *(Grus paradisea)*, Kori bustards *(Ardeotis kori)*, Griffon vultures *(Gypus fulvus)*, Short-toead snake eagles *(Circaetus gallicus)*, as well as three gull species (Martin et al., 2021, Martin & Katzir, 1999; Martin & Shaw 2010; Cantley et al., 2024).

Wing size, weight, speed and manoeuvrability in flight

Birds that are heavier and have with smaller wings relative to their mass (i.e. high wing loading), such as bustards, swans, divers and geese, and/or have broader, shorter wings (low aspect ratio), such as waterfowl, tend to have lower manoeuvrability in flight, making them more susceptible to collisions (Janss, 2000; Rubolini et al., 2015).

It follows then, that such birds are frequently reported as collision casualties. This increased risk stems from their higher flight speeds and reduced manoeuvrability. These factors are exacerbated by the fact that most birds are unable to slow down mid-flight, meaning that even if they are able to perceive an obstacle ahead, they are unlikely to be able to adapt their speed to avoid it (Martin, 2017). This becomes more acute for faster-flying birds, and under conditions which lessen the amount of visual information available (e.g. rain, mist, low light) (Martin, 2017).

Overview of avian morphology-related collision susceptibility

The below table provides the basis for the abridged table on page 2 of the Brochure. *Table 1* gives a more exhaustive list of bird groups, and an extensive bibliography of scientific research references used to assess the collision susceptibility of various bird species, grouped according to specific morphological traits. This table covers a range of morphological aspects, including body size, weight, flight speed, manoeuvrability, and a key sensory attribute: bird vision. It is important to note that while these research references address bird collision susceptibility, they do not imply comprehensive investigation of all species within the included families or groups.

Order	Families Investigated	Eye Morphology	Wing Morphology (size, weight, flight speed and manoeuvrability)
Pelecaniformes	Pelicans, Ibis and spoonbills	Silvman (1973), Schmidt-Morand (1992), Bevanger (1994)	APLIC (2012), Liesenjohann et al. (2019), NABU & RPS (2021)
	Herons, egrets, bittern	NABU & RPS (2021), Silvman, 1973, Schmidt-Morand (1992), Bevanger (1994)	Drewitt and Langston (2008), APLIC (2012), Liesenjohann et al. (2019), NABU & RPS (2021)
Gruiformes	Rails, gallinules, coots cranes	Frost (2008), Martin & Shaw (2010), Martin (2011), Liesenjohann et al. (2019), Bateman et al (2023)	Bevanger (1998), Janss (2000), Drewitt and Langston (2008), APLIC (2012), Bernardino et al (2018), D'Amico et al. (2019), Liesenjohann et al. (2019), NABU & RPS (2021)
Anseriformes	Waterfowl: Ducks, geese and swans	Jones et al. (2007), APLIC (2012)	D'Amico et al. (2019), Bevanger (1998)
Phoenicopteriformes	Flamingos		APLIC (2012), NABU & RPS (2021)
Charadriiformes	Sandpipers, plovers, snipes, phalaropes	Frost (2008)	Bevanger (1998), Janss (2000), Drewitt and Langston (2008), APLIC (2012), Bernardino et al. (2018), Liesenjohann et al. (2019), NABU & RPS (2021)
	Gulls and terns	Martin (2017)	Liesenjohann et al. (2019)
Podicipediformes	Grebes	APLIC (2012)	Bevanger (1998), APLIC (2012), Bernardino et al (2018), Liesenjohann et al. (2019)
Otidiformes	Bustards	Frost (2008), Martin (2010; 2011), Martin & Shaw (2010), Silva et al. (2023)	Janss (2000), Drewitt and Langston (2008), Barrientos et al. (2012), APLIC (2012), Bernardino et al (2018), NABU & RPS (2021), Silva et al. (2023)
Gaviiformes	Divers	APLIC (2012)	Bevanger (1998), Liesenjohann et al. (2019), NABU & RPS (2021)
Ciconiiformes	Storks	Martin & Shaw (2010), Martin (2011), Barrientos et al. (2012), NABU & RPS (2021)	Janss (2000), Liesenjohann et al. (2019), NABU & RPS (2021)
Suliformes	Gannets, cormorants, frigatebirds, boobies, anhingas	APLIC (2012)	Bevanger (1998), D'Amico et al. (2019), Liesenjohann et al. (2019)
Accipitriformes	Hawks, eagles, vultures, harriers	Martin (2011), Liesenjohann et al. (2019)	Janss (2000), APLIC (2012), Drewitt and Langston (2008)
Falconiformes	Falcons	Silman (1973), Schmidt-Morand (1992), Bevanger (1994), May et al. (2015)	

Columbiformes	Pigeons and doves		Bevanger (1998), APLIC (2012), Janss (2000), Drewitt and Langston (2008), Liesenjohann et al. (2019)
Strigiformes	Owls		
Galliformes	Landfowl: Grouse, pheasants, quail, partridges	Silvman (1973), Martin (2011), Linsey et al. (2012)	Bevanger (1998), Barrientos et al. (2012), Drewitt and Langston (2008), NABU & RPS (2021), Ammanat et al (2022)
Piciformes	Woodpeckers		Liesenjohann et al. (2019)
Passeriformes	Starlings, thrushes, warblers	Silman (1973), Schmidt-Morand (1992), Bevanger (1994), May et al. (2015)	
	Corvidae		Liesenjohann et al. (2019) Raptor Protection of Slovakia (2019)
Apodiformes	Swifts		

Table 1. Overview of avian morphology-related collision susceptibility and research references (adapted after Bateman et al., 2023a; b)

3.2 Avian behaviour factors influencing collision risk

Bird behaviour encompasses a range of activities including hunting, migration to courtship. Certain species-specific behavioural traits play a crucial role in determining their susceptibility to collisions with power lines. For example, scavenging near power lines exposes birds to heightened risk while foraging for food, while territorial defence behaviours can lead to rapid and unpredictable flights, increasing collision susceptibility for birds guarding their territory. Birds often engage in daily movements between feeding, breeding, and roosting sites, and these flights frequently occur during periods of low light, heightening the risk of collisions. While not limited to specific groups of birds, several studies suggest that less flight-affine juvenile birds are far more susceptible to collisions than adult birds (e.g. Crivelli et al., 1988; Brown & Drewien, 1995).

Flocking and gregariousness

It is generally understood that species that travel in large flocks may face elevated collision risks when navigating areas with numerous power lines (Bernadino et al., 2019). Flocking together in large numbers can increase chances of collisions with power lines due to constrained space available for manoeuvring, the heightened possibility of collisions within the group itself, and restricted vision for birds at the rear of the flock (Bevanger, 1998; Crowder, 2000; Janns, 2000; Crowder & Rhodes, 2002; Drewitt & Langston, 2008; Jenkins et al., 2010; APLIC 2012). This is particularly pronounced in species of waterfowl, wading birds, geese, cranes and bustards (APLIC, 2012).

Long distance migration

Whilst it is true that long distance migrating birds can fly huge distances without stopping, many long-distance migrants migrate at night, while resting and feeding during the day. Furthermore, it is important to consider that migrating birds traverse vast distances through unfamiliar, frequently changing territories, often in sizable flocks (D'Amico et al., 2018; Bateman et al., 2023b). This brings a certain degree of vulnerability, particularly acute for juvenile birds, who lack familiarity with flying and with the landscape's geographical features (Brown, 1993; Bevanger, 1994; Crowder & Rhodes, 2001 in Bateman et al., 2023b). These risks are intensified during stopovers, when birds fly at lower altitudes (APLIC, 2012; Bateman et al., 2023a).

Nocturnal birds and nocturnal migration

Collisions during the night occur more frequently because of diminished visibility of wires (D'Amico et al., 2018), which increases collision sensitivity for nocturnal birds such as owls (Bevanger, 1998; Rubolini et al., 2001). Species that migrate at night, such as songbirds, herons and bustards, can be particularly exposed to this risk (Janss, 2000; APLIC, 2012). This danger is exacerbated when adverse weather conditions oblige birds to fly at lower altitudes, where they are more likely to encounter obstacles (Bevanger, 1998; APLIC, 2012). In a 2016 study in Nebraska, USA, sensors known as 'Bird Strike Indicators'[22] were used to detect collision-related mortality of sandhill cranes *(Antigone canadensis)* and found that >95% of collisions occurred during the night.

Foraging and roosting trips

Foraging birds face heightened risks of collisions when their flight paths to and from their nests or colonies necessitate crossing power lines. The degree of this risk depends on the orientation of their foraging routes and the frequency with which they intersect these power lines. (APLIC, 2012). The need to feed offspring during the breeding season can lead birds to lengthen time periods spent hunting or foraging (and therefore also the flights between foraging and roosting locations), in turn increasing exposure to potential collision risk (Henderson et al., 1996, Bernadino et al. 2018, Bateman et al. 2023b). Collisions during the breeding season also deprive young birds of a parent, and thus reduce breeding success.

Aerial hunting

In the pursuit of prey, birds can face increase collision risk with power lines due to lowered spatial awareness in favour of a focus on the prey and increased speed, which implies lower reaction time (Bevanger 1998, Martin et al., 2012). Additionally, the prolonged duration of flight while hunting increases the probability of aerial predators encountering or inadvertently overlooking power lines (APLIC, 2012). By the same logic, courtship behaviours in the proximity of power lines are also understood to increase susceptibility of collision (ibid.).

Overview of avian behaviour-related collision susceptibility

In *Table 2*, we presented a more comprehensive list of bird groups and provide references which confirm that they exhibit behaviours which make them more susceptible to collision. The table encompasses various aspects of bird behaviour, such as flocking, migration, foraging and roosting and aerial hunting behaviours. However, the research references on bird collision susceptibility does not automatically mean that all species of the families/groups within the order column have been investigated for the issue of collision. Indeed, sometimes only certain focus species have been investigated. For detailed information please access specific research found in the bibliography.

[22] The Bird Strike Indicator (BSI) is an impulse-based vibration sensing and recording tool to detect bird strikes on aerial cables. For more information, see Harness et al., 2003 or the website of the developer, EDM Link.

Table 2. Overview of avian behaviour factors influencing collision-susceptibility according to research

Order	Families Investigated	Flocking	Feeding / Roosting Trips	Long Distance Migration	Nocturnal Birds and Night Migration	Aerial Hunters
Pelecaniformes	Pelicans, Ibis and spoonbills	Liesenjohann et al. (2019)	Crivelli et al (1988), APLIC (2012), Bernardino et al (2018), Bateman et al. (2023)	Bevanger (1998), Horton et al. (2019) Liesenjohann et al. (2019), Bateman et al. (2023)	Bateman et al. (2023)	
	Herons, egrets, bittern	Willard (1977), Bernardino et al (2018), Liesenjohann et al. (2019)	Willard (1977), APLIC (2012)	Horton et al. (2019), Liesenjohann et al. (2019)	APLIC (2012), Liesenjohann et al. (2019), Bateman et al. (2023)	
Gruiformes	Rails, gallinules, coots, cranes	APLIC (2012), Liesenjohann et al. (2019), Bateman et al. (2023)	Bateman et al. (2023)	Bevanger (1998), APLIC (2012), Horton et al. (2019), NABU & RPS (2021), Liesenjohann et al. (2019), Bateman et al (2023)	Drewitt and Langston (2008), APLIC (2012), Prinsen et al. (2011), Liesenjohann et al. (2019)	
Phoenicopteriformes	Flamingos	APLIC (2012), NABU & RPS (2021)	Bernardino et al. (2018)			
Anseriformes Waterfowl: Ducks, geese, swans, screamers (178)	Ducks, geese and swans	Faanes (1987), APLIC (2012), Prinsen et al. (2011), Bernardino et al. (2018), Liesenjohann et al. (2019)	Frost (2008)	APLIC (2012), Horton et al. (2019), Liesenjohann et al. (2019),	Horton et al. (2019), Liesenjohann et al. (2019)	
Charadriiformes	Sandpipers, plovers, snipes, phalaropes	Faanes (1987), APLIC (2012), Liesenjohann et al. (2019), Ammanat et al. (2022)		Bevanger (1998), APLIC (2012), Horton et al. (2019), Liesenjohann et al. (2019)	Bateman et al. (2023)	

	Gulls and terns	Faanes (1987), Bevanger (1998), APLIC (2012), Prinsen et al. (2011), Liesenjohann et al. (2019), Ammanat et al. (2022)	Bernardino et al. (2018), NABU & RPS (2021)	Bevanger (1998), APLIC (2012), Horton et al. (2019), Liesenjohann et al. (2019)	APLIC (2012), Horton et al. (2019), Liesenjohann et al. (2019)	
Podicipediformes	Grebes	APLIC (2012)		Horton et al. (2019)	APLIC (2012), Liesenjohann et al. (2019)	
Otidiformes	Bustards	Silva et al. (2022)	Silva et al. (2022)	Silva et al. (2022)	Silva et al. (2022)	
Gaviiformes	Divers	APLIC (2012), Liesenjohann et al. (2019)		Horton et al. (2019)	Horton et al. (2019)	
Ciconiiformes	Storks	Liesenjohann et al. (2019)		Bevanger (1998), Horton et al. (2019), Liesenjohann et al. (2019)	APLIC 2012, Liesenjohann et al. (2019)	
Suliformes	Gannets, cormorants, frigatebirds, boobies, anhingas	Liesenjohann et al. (2019)		Liesenjohann et al. (2019)		
Accipitriformes	Hawks, eagles, vultures, harriers		APLIC (2012)	Bevanger (1998), APLIC (2012), Horton et al. (2019)		Bevanger (1998), APLIC (2012)
Falconiformes	Falcons		Bateman et al. (2023)	Horton et al. (2019)		Bevanger (1998), APLIC (2012)
Columbiformes	Pigeons and doves	Prinsen et al. (2011), Bernardino et al. (2018), Liesenjohann et al. (2019), Bateman et al. (2023)		Horton et al. (2019), Liesenjohann et al. (2019), Bateman et al. (2023)	Liesenjohann et al. (2019)	
Strigiformes	Owls			Horton et al. (2019)	Bevanger (1998), Bateman et al. (2023)	
Galliformes	Landfowl: Grouse,				Liesenjohann et al. (2019)	

	pheasants, quail, partridges					
Piciformes	Woodpeckers			Horton et al. (2019), Liesenjohann et al. (2019)	Liesenjohann et al. (2019)	
Passeriformes	Starlings	APLIC (2012), Prinsen et al. (2011)			Bernardino et al. (2018)	
	Thrushes, warbles			Bevanger (1998), Horton et al. (2019)	Drewitt and Langston (2008), Prinsen et al. (2011), Bernardino et al. (2018), NABU & RPS (2021)	
	Swallows, martins	Drewitt and Langston (2008)		APLIC (2012)		APLIC (2012)
	Corvidae	Liesenjohann et al. (2019)		Horton et al. (2019), Liesenjohann et al. (2019)	Liesenjohann et al. (2019)	
Apodiformes	Swifts	Drewitt and Langston (2008)		Drewitt and Langston (2008), Horton et al. (2019)		Bevanger (1998), APLIC (2012)

3.3 Collision Sensitivity Indices

In the final column of this table, we present a selection of species which have been identified as highly susceptible to collision with power lines according to 'Collision Sensitivity Indices' of four peer-reviewed studies. The aim of including this column is to draw attention to representative species which, according to current research, are particularly susceptible to mortality by collision and hence, which may require particular attention should they occur in the vicinity of a power line. A comprehensive version of this table is available at the end of this section (see pages 52-63). The species which we selected to be included in the brochure are ones which reoccurred in the sensitivity indices of more than one study. These species are included in the table in bold.

Furthermore, in Annex I, we have summarised the methodology of Liesenjohann et al. (2019), which provides a 'similarity index' by which practitioners can use representative 'reference species' to understand the collision susceptibility of species for which there is no research available, and, in turn, to estimate the effectiveness of wire markers for that species. The full similarity index table is available in Annex II.

The methodologies of the studies vary from one another and are thus detailed below. For example, in some cases, the studies go beyond sensitivity to collision and consider other factors such as conservation status and potential population impact in their evaluations. The four studies we considered are:

- Bernotat & Dierschke (2021b): Overarching criteria for the assessment of wildlife mortality in the context of projects and interventions. Part II.1: Working aid for assessing the risk of collision of birds with overhead power lines. 4th version.
    - *Note: This study is only available in German. A summary in English is available under Annex I.*
- D'Amico et al. (2019): Bird collisions with power lines: Prioritizing species and areas by estimating potential population-level impacts.
- Gauld et al., (2022): Hotspots in the grid: Avian sensitivity and vulnerability to collision risk from energy infrastructure interactions in Europe and North Africa
- Silva et al., (2022): The effects of powerlines on bustards: how best to mitigate, how best to monitor?

The studies include extensive data from various countries across Europe (Germany, Spain, Portugal), Africa (Northern Africa, South Africa, Namibia), Asia (India, Iran, Kazakhstan, Mongolia, Russia, Uzbekistan, Cambodia), and Australasia. Collectively, we feel that these studies offer a relatively comprehensive analysis of collision-prone species, however we note that there remains a strong bias to Eurasian species.

Below, we offer short summaries of these studies, with a particular emphasis on their methodologies. For a thorough, species-specific breakdown from each study, please refer to *Table 3*, which provides an exhaustive list of the species analysed in these studies.

Study No. 1 – Bernotat & Dierschke (2021b): Overarching criteria for the assessment of wildlife mortality in the context of projects and interventions. Part II.1: Working aid for assessing the risk of collision of birds with overhead power lines. 4th version.

This pivotal study, first released in 2016 and updated in 2021, by the German Federal Agency for Nature Conservation (BfN), introduces for the first time a standardised, scientific classification system designed to assess species' mortality risk related to different types of human infrastructure (e.g., overhead power lines, roads, railways, wind turbines). While the system was initially designed only for birds, the method of scaling was adjusted to include other groups including all species of bats, amphibians and reptiles. Crucially, it also makes this knowledge available for the planning and impact assessment of infrastructure projects.

A major achievement of the study was the creation of a Mortality Sensitivity Index (MSI) *(Mortalitäts-Gefährungs-Index)* which enables an overall assessment of the species-specific significance of anthropogenic causes of mortality. This index is the result of the aggregation of two lower indices, namely the Population Biology Sensitivity Index (PSI) *(Populationsbiologischer Sensitivitäts-Index)*, which includes population trends and (natural) mortality rate, and Conservation Value Index (CVI) *(Naturschutzfachlicher Wert-Index)*, which includes conservation-related parameters (both PSI & CVI are detailed in Annex I). The MSI is a standardised assessment system which enables for the first time to derive the significance of the loss of an individual from a population with respect to conservational issues and decisions in environmental planning and assessments. In other words, the MSI allows one to detect for which species (being rare, threatened and sensitive) the loss of a few individuals is critical – or indeed less relevant (being abundant, non-threatened and generally 'robust').

In a next step, Bernotat & Dierschke developed a framework for classifying risk levels for certain species relative to different infrastructure types, to be known as a **'project-specific Mortality Sensitivity Index'** - hereafter pMSI *(*Vorhabentypspezifischer Mortalitäts-Gefährdungs-Index von Arten*)*. This was done by combining species' overall mortality sensitivity (MSI, as described in above), with understandings of their risk related to specific infrastructure types. In an initial phase, species' mortality risk per type of infrastructure (project-type-specific killing risk) was determined into a 5-level categorisation. This considered understanding of the species' biology and habits, data on the number of deceased animals associated with project types, expert assessments of factors of scale, and the authors' professional evaluations. This was based on an extensive research and analyses of German and European sources. In assessing potential risks to various species, parameters such as mobility, activity, flight behaviour, and visual capabilities play significant roles. Notably, factors like flight altitude, specialised behaviours during mating or hunting, and specific visual capabilities, especially frontal sight, are crucial. Mortality statistics were interpreted in the context of the species' frequency, the likelihood of carcass discovery (e.g., in forest or near water bodies) and reporting. All species for which carcass findings had been documented or species-specific assessments made or assumed to have at least a 'low' collision risk based on their group vulnerability (e.g., birds of prey), were considered based on their German Red List status. The potential discrepancy between found carcasses and actual fatality level – which is influenced by factors like bird size and habitat - is acknowledged, though correction factors for all species and project types was deemed not feasible. For very rare species, an absence of recorded carcass findings might necessitate the assessment of collision risk based on an extrapolation from birds with similar ecology and morphology. For common species, a lack of findings typically indicates a low project-type-specific risk. The focus was on regular breeding and guest bird species in Germany and bat species.

In a second phase, the project-type-specific killing risk was combined with the overall species' Mortality Sensitivity Index (MSI) to result in a project-type-specific Mortality Sensitivity Index (pMSI) (*vorhabentypspezifischer Mortalitäts Gefährdungs-Index*) - see Figure 2. This aggregated index combines understandings of project-type-specific killing risk with biological and conservation-related factors, interpretation of carcass statistics and thus establishes the significance of a project's risk factor for environmental planning. For example, it is known that birds such as the Mallard (*Anas platyrhynchos*), Wood pigeon (*Columba palumbus*), and Common starling (*Sturnis vulgaris)* frequently face casualties due to collisions with power lines. Yet, when this is considered alongside the MSI, the project-type-specific Mortality Sensitivity Index (pMSI) results in minor planning relevance for those species. The pMSI has been classified into five distinct levels: **very high sensitivity**; **high sensitivity**; **moderate sensitivity**; **low sensitivity;** and **very low sensitivity**.

- **Very High Risk (Tier 1)**: This tier includes species that are particularly susceptible to power line collisions, often indicated by disproportionately high fatality rates. Species like the Great bustard *(Otis tarda)*, Eurasian capercaillie *(Tetrao urogallus)* & Black-crowned night heron *(Nycticorax nycticorax)*, as well as many wading bird species fall into this category. These species typically have either poor manoeuvrability or a tendency to fly at heights where they are more likely to encounter power lines.
- **High Risk (Tier 2)**: This tier comprises species with significant, though slightly lower risk of collision compared to Tier 1, such as Common crane *(Grus grus)*, White stork *(Ciconia ciconia)*, Black stork *(Ciconia nigra)* and Northern Lapwing *(Vanellus vanellus)*. It includes additional wading bird species with fewer recorded fatalities than those in Tier 1, as well as birds like herons, geese, ducks, divers, terns, and some species of rails. These birds often have flight patterns or behaviours that increase their risk of collision.
- **Moderate Risk (Tier 3)**: This category consists of species that face a moderate risk of collision. Most gull species and some rail species, along with pigeons, thrushes and several birds of prey, are placed here. These birds have noticeable fatality numbers but are not as severely impacted as those in the higher tiers.
- **Low Risk (Tier 4)**: Species in this tier, such as some corvids (e.g. crows and ravens), as well as certain songbirds with higher recorded fatalities, face a less severe risk of collision in terms of pMSI.
- **Very Low Risk (Tier 5)**: This final tier includes species for which the risk of collision is minimal. These are birds that, despite their relative abundance, have very few recorded instances of collision. They are either adept at avoiding power lines or do not typically fly at the heights where collisions are common.

For more detail on this methodology, as well as a full table of birds with a pMSI ranking from very high to moderate, see Annex I.

The methodology is dynamic and responsive to new research and changes in bird populations. It integrates updated criteria from sources like BirdLife International and the latest Red Lists from various federal states, ensuring that the risk assessments remain current and reflective of the latest scientific understanding. Indeed, with the 2021 revision of this work, certain species changed in their rankings.

Table 3. Breeding & resident birds for Germany at higher risk of collision with power lines according to project-specific Mortality Sensitivity Index (pMSI) (translated from Bernotat & Dierschke, 2021b)

	pMSI levels		
Species groups	**Very high**	**High**	**Moderate**
Bustards	Great bustard (Otis tarda)		
Storks, Cranes		Common crane (Grus grus), White stork (Ciconia ciconia), Black stork (Ciconia nigra)	
Herons	Black-crowned night heron (Nycticorax nycticorax)	Common spoonbill (Platalea leucorodia), Common bittern (Botaurus stellaris), Little bittern (Ixobrychus minutus), Great white egret (Ardea alba), Purple heron (Ardea purpurea)	Grey heron (Area cinerea)
Waders & sandpipers	Eurasian curlew (Numenus arquata), Black-tailed godwit (Limosa limosa), Eurasian golden plover (Pluvialis apricaria), Common snipe (Gallinago gallinago), Ruff (Philomachus pugnax), Common redshank (Tringa totanus), Dunlin (Calidris alpina), Common sandpiper (Actitis hypoleucos), Stone curlew (Burhinus oedicnemus), Ringed plover (Charadrius hiaticula), Kenitsh plover (Caradrius alexandrines), Ruddy turnstone (Arenaria interpres)	Northern lapwing (Vanellus vanellus), Eurasian oystercatcher (Haematopus ostralegus), Wood sandpiper (Tringa glareola), Black-winged stilt (Himantopus himantopus), Pied avocet (Recurvirostra avosetta)	Green sandpiper (Tringa ochropus), Little ringed plover (Charadrius dubius), Eurasian woodcock (Scolopax rusticola)
Gamebirds	Black grouse (Lyrurus tetrix syn. Tetrao tetrix), Eurasian capercaillie (Tetrao urogallus)	Ptarmigan (Lagopus muta)	Hazel grouse (Tetrastes bonasia), Rock partridge (Alectoris graeca), Grey partridge (Perdix perdix), European quail (Coturnix coturnix)
Swans		Whooper swan (Cygnus cygnus)	Mute swan (Cygnus olor)
Geese			Barnacle goose (Branta leucopsis), Greylag goose (Anser anser), Common shelduck (Tadorna tadorna)
Ducks	Greater scaup duck (Aythya marila)	Eurasian wigeon (Anas penelope), Garganey (Spatula querquedula syn. Anas querquedula), Eurasian teal (Anas crecca), Northern shoveller	Mallard (Anas platyrhynchos),

		(Anas clypeata), Eurasian pochard (Aythya ferina), Ferruginous duck (Aythya nyroca), Northern pintal (Anas acuta)	
Divers	Horned grebe (Podiceps auritus)	Red-necked grebe (Podiceps grisegena), Black-necked grebe Podiceps nigricollis)	Great crested grebe (Podiceps cristatus), Little grebe (Tachybaptus ruficollis)
Mergansers		Goosander (Merugs merganser)	Red-breasted merganser (Mergus serrator)
Rails		Corncrake (Crex crex), Spotted crake (Porzana porzana), Little crake (Porzana parva), Baillon's crake (Porzana pusilla)	Water rail (Rallus aquaticus), Common moorhen (Gallinula chloropus), Eurasian coot (Fulica atra)
Gulls	Little gull (Hydrocoloeus minutus sny. Larus minutus)	Great black-backed gull (Larus marinus), Black-legged kittiwake (Rissa tridactyla)	Black-headed gull (Chroicocephalus ridibundus), European herring gull (Larus argentatus), Yellow-legged gull (Larus michahellis), Caspian gull (Larus cachinnans)
Terns		Common tern (Sterna hirundo), Black tern (Chlidonias niger), Arctic tern (Sterna paradisaea), Little tern (Sternula albifrons), Sandwich tern (Thalasseus sandvicensis), Caspian tern (Hydroprogne caspia), Gull-billed tern (Gelochelidon nilotica)	Whiskered tern (Chlidonias hybrida), White-winged black tern (Chlidonias leucopterus)
Birds of prey	European lesser spotted eagle (Clanga pomarina), Golden eagle (Aquila chrysaetos)	Osprey (Pandion haliaetus), Greater spotted eagle (Aquila clanga), Hen harrier (Circus cyaneus)	Montagu's harrier (Circus pygargus), Eurasian marsh harrier (Circus aeruginosus), Eurasian hobby (Falco Subbuteo), European honey buzzard (Pernis apivorus)
Owls			Eurasian eagle owl (Bubo bubo), Ural owl (Strix uralensis), Little owl (Athene noctua), Eurasian scops owl (Otus scops), Short-eared owl (Asio flammeus)
Doves			Woodpigeon (Columba palumbus), Eurasian turtle dove (Streptopelia turtur)
Thrushes & starlings			Ring ouzel (Turdus torquatus), Common starling (Sturnus vulgaris)
Corvids			Common raven (Corvus corax), Alpine chough (Pyrrhocorax graculus)

Table 4. Migrant birds for Germany at higher risk of collision with power lines according to project-specific Mortality Sensitivity Index (pMSI) (translated from, Bernotat & Dierschke, 2021)

	pMSI levels		
Species groups	**Very high**	**High**	**Moderate**
Storks, Cranes		White stork (Ciconia ciconia), Black stork (Ciconia nigra)	Common crane (Grus grus)
Herons		Common spoonbill (Platalea leucorodia), Common bittern (Botaurus stellaris), Little bittern (Ixobrychus minutus), Black-crowned night heron (Nycticorax nycticorax)	Grey heron (Area cinerea),) Great white egret (Ardea alba), Purple heron (Ardea purpurea), Little egret (Egretta garzetta)
Waders & sandpipers	Eurasian stone curlew (Burhinus oedicnemus), Common redshank (Tringa totanus)	Northern lapwing (Vanellus vanellus), Eurasian oystercatcher (Haematopus ostralegus), Kenitsh plover (Caradrius alexandrines), Eurasian dotterel (Eudromias morinellus), Eurasian whimbrel (Numenius phaeopus), Eurasian curlew (Numenus arquata), Black-tailed godwit (Limosa limosa), Bar-tailed godwit (Limosa lapponica), Jacksnipe (Lymnocryptes minimus), Great snipe (Gallinago media), Common snipe (Gallinago gallinago), Common redshank (Tringa totanus), Ruff (Calidris pugnax), Broad-billed sandpiper (Limicola falcinellus), Curlew sandpiper (Calidris ferruginea), Purple sandpiper (Calidris maritima), Dunlin (Calidris alpina)	Pied avocet (Recurvirostra avosetta), Black-bellied plover (Pluvialis squatarola), Eurasian golden plover (Pluvialis apricaria), Little ringed plover (Charadrius dubius), Common ringed plover (Charadrius hiaticula), Eurasian woodcock (Scolopax rusticola), Spotted redshank (Tringa erythropus), Northern Phalarope (Phalaropus lobatus), Common greenshank (Tringa nebularia), Green sandpiper (Tringa ochropus), Marsh sandpiper (Tringa stagnatilis), Wood sandpiper (Tringa glareola), Ruddy turnstone (Arenaria interpres), Great knot (Calidris tenuirostris), Sanderling (Calidris alba), Little stint (Calidris minuta), Temminck's stint (Calidris temminckii)
Gamebirds			European quail (Coturnix coturnix)
Swans		Whooper swan (Cygnus cygnus), Bewick's swan (Cygnus columbianus)	Mute swan (Cygnus olor)
Geese	Lesser white-fronted goose (Anser erythropus)	Taiga bean goose (Anser fabalis), Pink-footed bean goose (Anser brachyrhynchus)	Brent goose (Branta gernicla) Barnacle goose (Branta leucopsis), Tundra bean goose (Anser serrirostris), Greylag goose (Anser anser), Greater white-fronted goose (Anser albrifrons)
Ducks	Greater scaup duck	Ferruginous duck (Aythya nyroca), Common eider duck (Somateria mollissima), Eurasian white-winged scoter (Melanitta fusca)	Gadwall (Mareca strepera), Eurasian teal (Anas crecca), Eurasian wigeon (Anas penelope),

	(Aythya marila)		Mallard (Anas platyrhynchos), Northern pintal (Anas acuta), Garganey (Spatula querquedula syn. Anas querquedula), Northern shoveller (Anas clypeata), Eurasian pochard (Aythya ferina), Tufted duck (Aythya fuligula), Greater scaup (Aythya marila), Long-tailed duck (Clangula hyemalis), Common scoter (Melanitta nigra), Common goldeneye (Bucephala clangula)
Divers	White-billed diver (Gavia adamsii)	Red-necked grebe (Podiceps grisegena), Horned grebe (Podiceps auritus), Red-throated diver (Gavia stellata), Great northern diver (Gavia immer), Black-throated diver (Gavia arctica)	Great crested grebe (Podiceps cristatus), Little grebe (Tachybaptus ruficollis), Black-necked grebe (Podiceps nigricollis)
Mergansers			Smew (Mergellus albellus), Goosander (Merugs merganser), Red-breasted merganser (Mergus serrator)
Rails		Baillon's crake (Porzana pusilla)	Water rail (Rallus aquaticus), Corncrake (Crex crex), Spotted crake (Porzana porzana), Little crake (Porzana parva), Common moorhen (Gallinula chloropus), Eurasian coot (Fulica atra)
Gulls		Arctic skua (Sterocorarius parasiticus), Lesser black-backed gull (Larus fuscus), Black-legged kittiwake (Rissa tridactyla)	Long-tailed skua (Stercorarius longicaudus), Pomarine skua (Stercorarius pomarinus), Great skua (Stercorarius skua), Little gull (Hydrocoloeus minutus sny. Larus minutus, Black-headed gull (Chroicocephalus ridibundus), Mediterranean gull (Larus melanocephalus), Common gull (Larus canus), Great black-backed gull (Larus marinus), European herring gull (Larus argentatus), Yellow-legged gull (Larus michahellis)
Terns		Gull-billed tern (Gelochelidon nilotica), Black tern (Chlidonias niger)	Whiskered tern (Chlidonias hybrida), White-winged black tern (Chlidonias leucopterus), Common tern (Sterna hirundo), Arctic tern (Sterna paradisaea), Little tern (Sternula albifrons), Sandwich tern (Thalasseus sandvicensis), Caspian tern (Hydroprogne caspia)
Birds of prey		European lesser spotted eagle (Clanga pomarina), Short-toed snake eagle (Carcaetus gallicus)	Golden eagle (Aquila chrysaetos), White-tailed eagle (Haliaeetus albicilla), Osprey (Pandion haliaetus), Hen harrier (Circus cyaneus), Red kite (Milvus milvus), Rough-legged buzzard (Buteo lagopus), Red-footed falcon (Falco vespertinus)
Owls			Short-eared owl (Asio flammeus)
Doves			Eurasian turtle dove (Streptopelia turtur)
Thrushes & starlings			Ring ouzel (Turdus torquatus)
Corvids			Common raven (Corvus corax)

Study No. 2 – Bird collisions with power lines: Prioritising species and areas by estimating potential population-level impacts from D'Amico et al. (2019)

The research article by D'Amico and colleagues presents a method to prioritise bird species and areas based on the risk of collision with power lines, focusing on potential impacts at the population level. The study is centred on resident breeding birds in Spain and Portugal. The authors developed a species prioritisation method integrating morpho-behavioural susceptibility to collision, susceptibility to extinction, and spatial exposure to power lines.

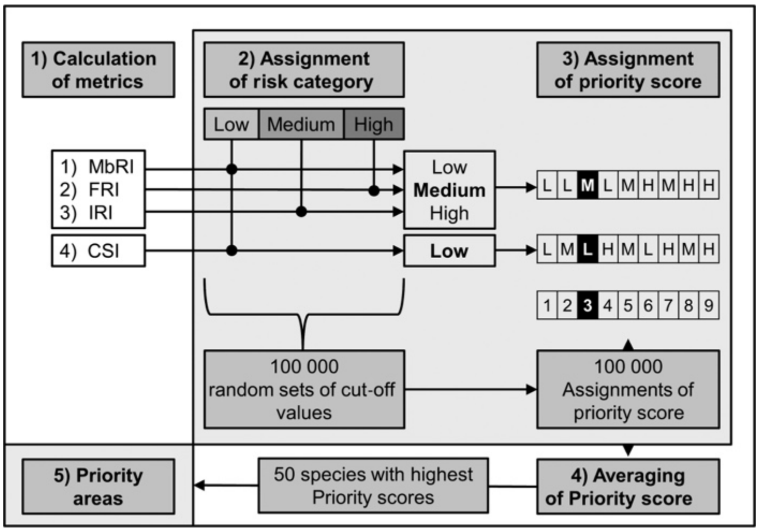


Figure 10. Prioritisation workflow in five steps (D'Amico et al., 2019)

They collected data on bird species' distribution and transmission power lines in the two countries and calculated various key metrics to assess collision risk and conservation status. Making use of simulation modules it was possible to categorise risk levels, and priority scores were assigned to species. The metrics included were:

- Morpho-behavioural Risk Index (MbRI): A new metric designed to account for species' susceptibility to collision with power lines considering both morphological and behavioural traits. Species with high MRI tend to have low manoeuvrability in flight and peripheral vision. The highest MRI – greatest susceptibility to collision - was given to the Great bustard *(Otis tarda)*.
- Fatality Risk Index (FRI): A measure of Population Exposure to Collision with power lines (PEC) and species extinction risk due to life-history traits related to breeding history. The species with the highest FRI in Spain and Portugal were the European short-toed snake-eagle *(Circaetus gallicus)* and Eurasian griffon vulture *(Gyps fulvus)* respectively.
- Indirect Risk Index (IRI): A measure of both PEC and species extinction risk due to life-history traits related to habitat selection. The species with highest IRI in Spain and Portugal were the Tufted duck *(Aythya fuligula)* and the Western marsh-harrier *(Circus aeruginosus)* respectively.

- Conservation Status Index (CSI): A measure of general extinction risk for all considered species, ranking from 1 = Least Concern and Data Deficient to 5 = Critically Endangered. Species with the highest CSIs in Spain and Portugal include the Ferruginous pochard *(Aythya nyroca)* and Eurasian cinerous vulture *(Aegypius moachus)* respectively.

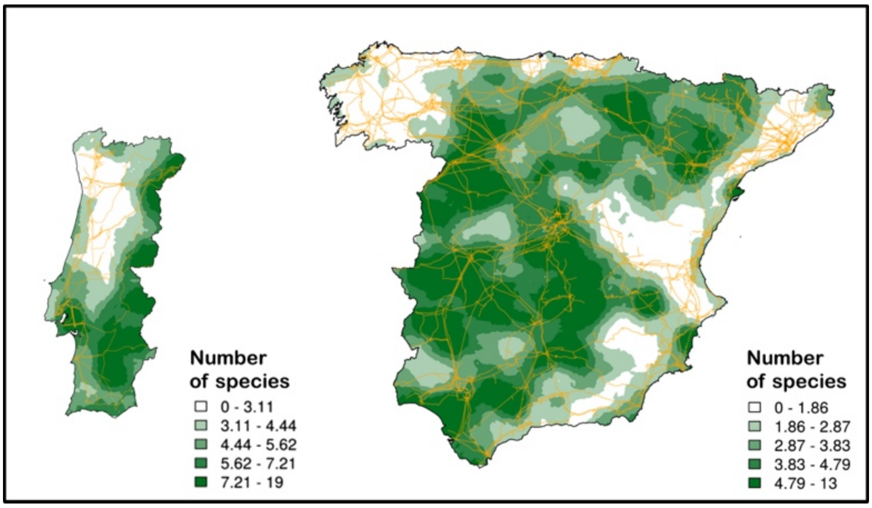


Figure 11. Identification of priority areas for collision mitigation in Spain and Portugal (D'Amico et al., 2019)

The results identified large, long-lived, slow-reproducing birds, often habitat specialists, as most susceptible to collision and mapped geographic hotspots for extinction risk due to collisions with power lines in both Spain and Portugal. The most sensitive species (i.e. with the highest extinction risk due to potential collision with power lines) was the Osprey *(Pandion haliaetus)* for Spain and the Red-billed chough *(Pyrrhocorax pyrrhocorax)* for Portugal. The study's observed differences between Spain and Portugal are due to a unique mix of some resident breeding species in Spain, which are not found in Portugal, though all species present in Portugal are also present in Spain. Additionally, Spain has a denser network of transmission power lines, leading to higher fatality and risk indices compared to Portugal. Moreover, the conservation status of species is more critical in Portugal than in Spain, reflecting heightened conservation concerns.

The study's insights show that the method helps in identifying species and areas with high extinction risks due to power line collisions and can be applied globally wherever data on power-line distribution and species information are available. The study provides a framework for prioritising conservation efforts, identifying areas needing urgent mitigation measures, and assisting in planning new power infrastructure to minimise impacts on bird populations.

Study No. 3 – Gauld et al., (2022): Hotspots in the grid: Avian sensitivity and vulnerability to collision risk from energy infrastructure interactions in Europe and North Africa

The comprehensive study on avian sensitivity and vulnerability to collision risks with energy infrastructure focuses on overhead power lines and wind turbines, across Europe and North Africa. It presents an in-depth understanding of the challenges various bird species face in these regions. The research employs a multifaceted methodology to assess the impact on birds, blending GPS tracking data with various environmental and ecological metrics to identify high-vulnerability 'hot-spots' for avian sensitivity and vulnerability to collision risk.

This research is pivotal in highlighting the species that are most susceptible to these threats and pinpointing the regions where these risks are most pronounced, hence where planning and risk mitigation should be most careful to avoid further impacts and reduce existing risk for vulnerable populations. Geographically, the study spans across Europe and North Africa, giving particular attention to key migratory bottlenecks such as the Strait of Gibraltar and the Bosporus Strait. These areas are critical as they are major migration routes for a multitude of bird species.

The methodology behind the assessment of bird collision risks with overhead power lines involves a detailed analysis of GPS tracking data from 1,454 birds across 27 species. The study determined the danger height for power lines to be between 10 and 60 meters. It then calculated the proportion of GPS flight locations within this danger height for each species in each grid cell. The study sorts the risk of birds colliding with power lines or wind turbines into different levels based on how often birds fly at dangerous heights in different areas. These areas are divided into grid cells, and each cell is given a score based on how risky it is for birds:

1) **Very High Risk**: These areas are among the top 2.5% most dangerous places, meaning they have a lot of birds flying at dangerous heights.
2) **High Risk**: These areas are riskier than most.
3) **Moderate Risk**: These are areas with an average amount of risk.
4) **Low Risk**: These areas have some danger, but less than what is found in most places.
5) **Very Low Risk**: These areas have birds flying around, but not at heights where they might hit power lines or wind turbines.

If there was no data for an area, it was marked as 'No Data', and the study points out that just because an area doesn't have a high-risk score, it doesn't mean there's no danger there—it might just mean they don't have enough information about that area.

In defining sensitivity to collision, the study used a Morpho-Behavioural Risk Index (MbRI), based on the method used in D'Amico et al. (2019) (see above), incorporating factors like wing-body mass ratio, flight style, vision type, and nocturnal activity, along with the European conservation status of the species. By overlaying the sensitivity values with the density of existing power lines, the study was able to determine a vulnerability score. This score is a measure of how exposed individuals are to the presence of energy infrastructure (power lines or wind turbines) in horizontal and vertical space, and how sensitive they are to the collision risks posed by this infrastructure. This score indicates the potential risk of collision for each bird species in different geographic areas, providing a nuanced understanding of where mitigation efforts should be focused.

Across European and North Africa, 9.41% of grid cells classified as 'high sensitivity'. Regarding sensitivity at the transmission power line danger height, the five most sensitive species identified were Eurasian spoonbill *(Platalea leucorodia)*, Eurasian eagle owl *(Bubo bubo)*, Whooper swan *(Cygnus cygnus)*, Iberian imperial eagle *(Aquila adalberti)*, and White stork *(Ciconia ciconia).* In the table at the end of this chapter, the number in brackets refers to the number of high-vulnerability grid cells (vulnerability hotspots) associated with power lines for a particular species.

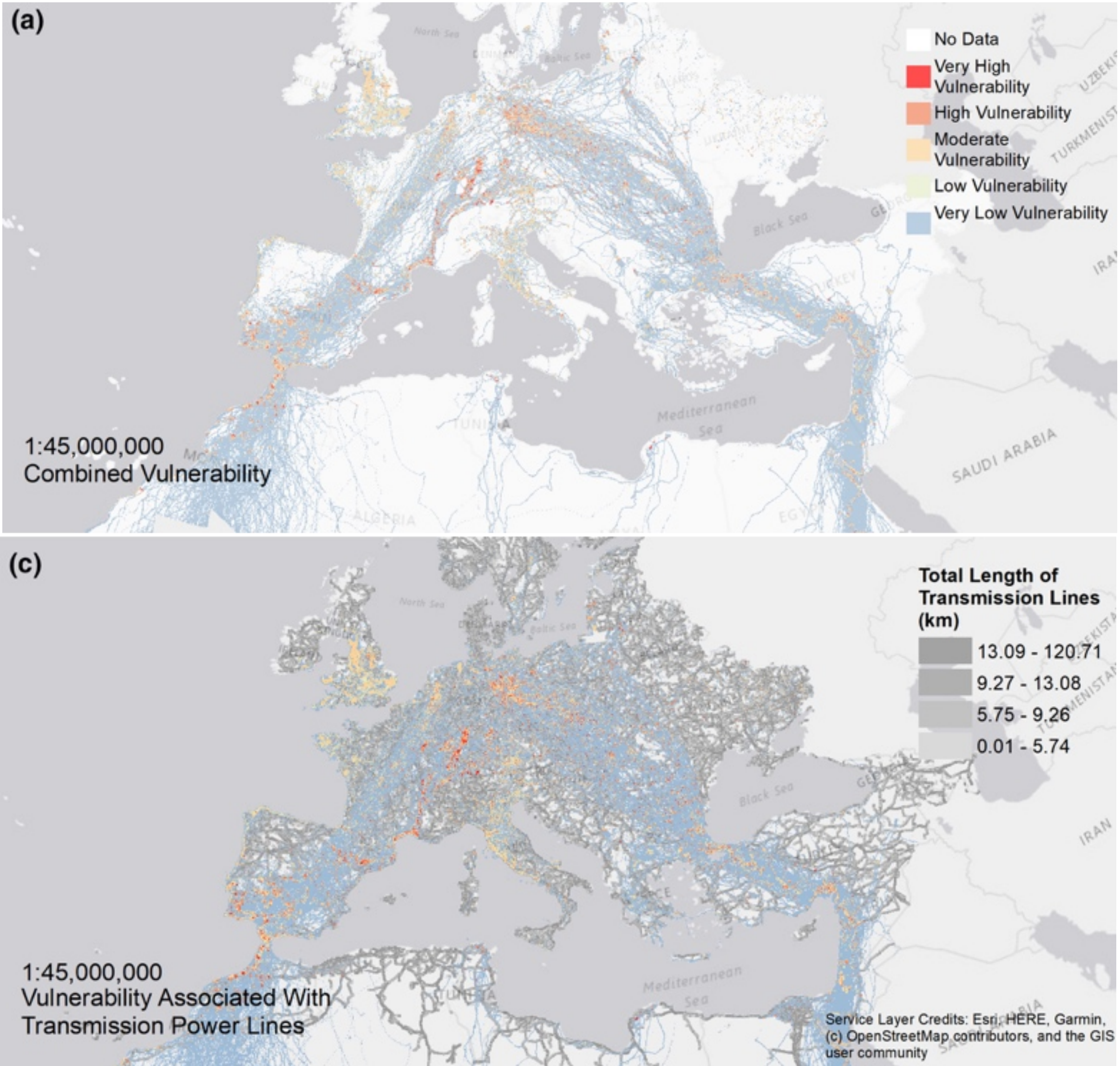


Figure 12. Hotspots where the GPS tracked birds (N = 1,454) are most vulnerable to risks associated with transmission power lines. Grey grid cells in panels b and c represent the density of EI in grid cells for which we do not have sufficient tracking data and as such represent areas of unknown vulnerability. Vulnerability categories are symbolised as per the legend in panel a. Basemap from (OpenStreetMap, 2019b). Adapted from Gauld et al., 2022.

Study No. 4 – Silva et al., (2022): The effects of powerlines on bustards: how best to mitigate, how best to monitor?

This comprehensive study sought to scrutinise the intricate relationship between power lines and the well-being of bustards, a family of large and threatened birds. Recognising the critical status of these birds and their susceptibility to power line collisions, the study set out with the clear objective of assessing the extent of mortality due to power lines and evaluating the efficacy of measures designed to mitigate these risks.

The methodological approach involved a systematic review of a wealth of both published and unpublished literature up until January 2021. Utilising established databases like ISI Web of Knowledge (which provides access to current and retrospective multidisciplinary information from approximately 8,500 of the most well-known global research journals) and Scopus (a source-neutral abstract and citation database curated by independent subject matter experts), the researchers checked through relevant studies, while also engaging with professionals in the field to gather comprehensive data. This approach ensured a broad spectrum of information, encompassing various geographical regions and perspectives on the issue.

The scope of the study was global, as it included a diverse array of bustard species. Prominent among these were the Great bustard *(Otis tarda)*, Little bustard *(Tetrax tetrax)*, Kori bustard *(Ardeotis kori)*, and the critically endangered Great Indian bustard *(Ardeotis nigriceps)*. Additionally, the study covered the Asian Houbara *(Chlamydotis macqueenii)*, African Houbara *(Chlamydotis undulata)*, Bengal Florican *(Houbaropsis bengalensis)*, Lesser Florican *(Sypheotides indicus)*, along with several others, each facing unique challenges related to power line collisions. These bustards can be found in the African, Asian, European, and Australian continent. Collisions with power lines represent the major threat pushing some bustard species towards extinction, particularly the Great Indian bustard and the Bengal Florican, both critically endangered, along with the endangered Ludwig's Bustard *(Neotis ludwigii)*. These findings underscore the urgency of targeted conservation efforts and mitigation strategies to protect these vulnerable species from further decline.

The results of the study revealed 2,774 recorded instances of bustard collisions with power lines, impacting 14 different species. This data underscored the severe threat posed by power lines to these birds. In terms of mitigation, the study found that the most effective solution is the burial of power lines, although other strategies like rerouting and power line design modifications also play a crucial role. Concerningly, the effectiveness of wire markers was observed to be limited for bustards.

The study also highlighted significant gaps and needs in terms of monitoring and research. It emphasised the critical importance of systematic carcass surveys, along with necessary bias corrections, for accurately assessing the impact of power lines. The need for more rigorous evaluations of mitigation measures and further research into the overall population effects of electricity grids on bustards was clearly outlined. The data from the study are centred around collecting collision event data from various countries and include the 2021 IUCN status for each bustard species, covering categories such as CR (Critically Endangered), EN (Endangered), VU (Vulnerable), NT (Near Threatened), and LC (Least Concern).

The study concluded with a set of conservation recommendations, including targeted strategic planning in power line construction, the use of habitat management to mitigate collision risks, and emphasised the importance of long-term monitoring of bustard populations. This narrative underscores the complex challenges faced by conservationists and power companies alike and calls for collaborative efforts to mitigate the risks power lines pose to bustard species. For a full list of the bustard species, see table 9 below or visit the study.

Table 5. An overview of all species included in the Collision Sensitivity Indices of Bernotat & Dierschke (2021b); D'Amico et al., 2019; Gauld et al.; Silva et al., (2022). Species listed in bold are those which reoccurred in more than one index and were thus included in the brochure.

		Bernotat & Dierschke (2021b) Project-specific Mortality Sensitivity Index (pMSI) of breeding, resident & migrant birds for collision with power lines (relevant for Germany)			**D'Amico et al. (2019)** Collision Sensitivity Index (n) = priority score		**Gauld et al. (2022)** Collision Sensitivity Index (n = no. high vulnerability grid cells with powerlines for species)	**Silva et al. (2022)** Summary of collision events with power lines by bustard species (n = no. of collisions observed from study or expert data)
Order	**Common bird groups**	**Very high**	**High**	**Moderate**	**Spain**	**Portugal**		
Pelecani formes	Pelicans, Ibis and spoonbills		Eurasian spoonbill (Platalea leucorodia)		Eurasian spoonbill (Platalea leucorodia) (18), Glossy ibis (Plegadis falcinellus) (38)	Eurasian spoonbill (Platalea leucorodia) (11)	Northern bald ibis (Geronticus eremita) (217), Eurasian spoonbill (Platalea leucorodia) (5)	
	Herons, egrets, bittern	Black-crowned night heron (Nycticorax nycticorax)	Common bittern (Botaurus stellaris), Little bittern (Ixobrychus minutus), Great white egret (Ardea alba), Purple heron (Ardea purpurea)	Grey heron (Area cinerea) - Great white egret (Ardea alba), Purple heron (Ardea purpurea), Little egret (Egretta garzetta)	Eurasian bittern (Botaurus stellaris) (8), Black-crowned night heron (Nycticorax nycticorax) (32)	**Black-crowned night heron (Nycticorax nycticorax)** (5), Squacco heron (Ardeola ralloides) (4), **Purple heron (Ardea purpurea)** (20) **Little bittern (Ixobrychus minutus)** (47)	N/A	

Gruiformes	Rails, gallinules, coots, cranes		Eurasian crane (Grus grus), Corncrake (Crex crex), Spotted crake (Porzana porzana), Little crake (Porzana parva), Baillon's crake (Porzana pusilla)	Hazel grouse (Tetrastes bonasia), Rock partridge (Alectoris graeca), Grey partridge (Perdix perdix), European quail (Coturnix coturnix), Water rail (Rallus aquaticus), Common moorhen (Gallinulla chloropus), Eurasian coot (Fulica atra) - European quail (Coturnix coturnix), Corncrake (Crex crex), Spotted crake (Porzana porzana), Little crake (Porzana parva)	Crested coot (Fulica cristata) (7)	Western swamphen (Porphyrio porphyrio) (31),	Eurasian crane (Grus grus) (362)	
Anseriformes	Waterfowl: Ducks, geese, swans, sawbills	Greater scaup duck (Aythya marila) - Lesser white-fronted goose (Anser erythropus)	Whooper swan (Cygnus cygnus), Eurasian wigeon (Anas penelope), Garganey (Spatula querquedula syn. Anas querquedula), Eurasian teal (Anas crecca), Northern shoveller (Anas clypeata), Eurasian pochard (Aythya omari), Ferruginous	Mallard (Anas platyrhnychos), Barnacle goose (Branta leucopsis), Greylag goose (Anser anser), Common shelduck (Tadorna tadorna), Red-breasted merganser (Mergus serrator) - Brent goose (Branta gernicla) Tundra bean goose (Anser serrirostris) Greater white-fronted goose (Anser albrifrons), Gadwall (Mareca	**Ferruginous duck (Aythya nyroca)** (3), Marbled duck (Marmaronetta angustirostris) (6), White-headed duck (Oxyura leucocephala) (11), Red-crested pochard (Netta rufina) (12), **Garganey (Spatula querquedula syn. Anas querquedula)** (27), Common shelduck (Tardona tardona) (34), Tufted duck	Common pochard (Aythya ferina) (8), Red-crested pochard (Netta rufina) (25), Northern shoveler (Spatula clypeata) (26), **Common shelduck (Tadorna tadorna)** (38) Gadwall (Mareca strepera) (42) **Mallard (Anas platyrhynchos)** (45)	Mallard (Anas platyrhnychos) (5), Eurasian wigeon (Mareca penelope) (0), White-fronted goose (Anser albifrons) (5), Barnacle goose (Branta leucopsis) (4), Whooper Swan (Cygnus cygnus) (29)	

			duck (Aythya nyroca), Northern pintal (Anas acuta) - Bewick's swan (Cygnus columbianus), Taiga bean goose (Anser fabalis), Pink-footed bean goose (Anser brachyrhynchus) , Ferruginous duck (Aythya nyroca), Common eider duck (Somateria mollissima), Eurasian white-winged scoter (Melanitta fusca)	strepera), Eurasian teal (Anas crecca), Eurasian wigeon (Anas penelope), Northern pintal (Anas acuta), Garganey (Spatula querquedula syn. Anas querquedula), Northern shoveller (Anas clypeata), Eurasian pochard (Aythya ferina), Tufted duck (Aythya fuligula), Greater scaup (Aythya marila), Long-tailed duck (Clangula hyemalis), Common scoter (Melanitta nigra), Common goldeneye (Bucephala clangula), Smew (Mergellus albellus), Goosander (Mergus merganser)	(Aythya fuligula) (37), Mallard (Anas platyrhynchos) (43), Common pochard (Aythya ferina) (44), **Northern pintail (Anas acuta)** (45), **Northern shoveler (Spatula clypeata)** (48)			
Charadriiformes	Waders/shorebirds: Sandpipers, plovers, snipes, phalaropes	Eurasian curlew (Numenus arquata), Black-tailed godwit (Limosa limosa), Eurasian golden plover (Pluvialis apricaria), Common snipe (Gallinago gallinago), Ruff (Philomachus pugnax),	Northern lapwing (Vanellus vanellus), Eurasian oystercatcher (Haematopus ostralegus), Wood sandpiper (Tringa glareola), Black-winged stilt (Himantopus	Green sandpiper (Tringa ochropus), Little ringed plover (Charadrius dubius), Eurasian woodcock (Scolopax rusticola) - Pied avocet (Recurvirostra avosetta), Black-bellied plover (Pluvialis squatarola), Eurasian golden plover (Pluvialis	**Kentish plover (Anarhynchus alexandrinus)** (31), Common snipe (Gallinago gallinago) (21), **Stone-curlew (Burhinus oedicnemus)** (49)	Redshank (Tringa totanus) (9), Common snipe (Gallinago gallinago) (13), Pied avocet (Recurvirostra avosetta) (37), Common sandpiper (Actitis hypoleucos) (41) Eurasian stone-curlew (Burhinus	Eurasian stone curlew (Burhinus oedicnemus) (0)	

		Common redshank (Tringa totanus), Dunlin (Calidris alpina), Common sandpiper (Actitis hypoleucos), Stone curlew (Burhinus oedicnemus), Ringed plover (Charadrius hiaticula), Kenitsh plover (Caradrius alexandrines), Ruddy turnstone (Arenaria interpres) - Eurasian stone curlew (Burhinus oedicnemus), Common redshank (Tringa totanus)	himantopus), Pied avocet (Recurvirostra avosetta), Kenitsh plover (Caradrius alexandrines), Eurasian dotterel (Eudromias morinellus), Eurasian whimbrel (Numenius phaeopus), Eurasian curlew (Numenus arquata), Black-tailed godwit (Limosa limosa), Bar-tailed godwit (Limosa lapponica), Jacksnipe (Lymnocryptes minimus), Great snipe (Gallinago media), Common snipe (Gallinago gallinago), Common redshank (Tringa totanus), Ruff (Calidris pugnax), Broad-billed sandpiper (Limicola	apricaria), Little ringed plover (Charadrius dubius), Common ringed plover (Charadrius hiaticula), Eurasian woodcock (Scolopax rusticola), Spotted redshank (Tringa erythropus), Northern Phalarope (Phalaropus lobatus), Common greenshank (Tringa nebularia), Green sandpiper (Tringa ochropus), Marsh sandpiper (Tringa stagnatilis), Wood sandpiper (Tringa glareola), Ruddy turnstone (Arenaria interpres), Great knot (Calidris tenuirostris), Sanderling (Calidris alba), Little stint (Calidris minuta), Temminck's stint (Calidris temminckii)		oedicnemus) (44)		

			falcinellus), Curlew sandpiper (Calidris ferruginea), Purple sandpiper (Calidris maritima), Dunlin (Calidris alpina)					
	Gulls, tern, auks and skuas	Little gull (Hydrocoloeus minutus sny. Larus minutus)	Common tern (Sterna hirundo), Black tern (Chlidonias niger), Arctic tern (Sterna paradisaea), Little tern (Sternula albifrons), Sandwich tern (Thalasseus sandvicensis), Caspian tern (Hydroprogne caspia), Gull-billed tern (Gelochelidon nilotica) - Arctic skua (Sterocorarius parasiticus), Lesser black-	Black-headed gull (Chroicocephalus ridibundus), European herring gull (Larus argentatus), Yellow-legged gull (Larus michahellis), Caspian gull (Larus cachinnans),Whiskered tern (Chlidonias hybrida), White-winged black tern (Chlidonias leucopterus) - Long-tailed skua (Stercorarius longicaudus), Pomarine skua (Stercorarius pomarinus), Great skua (Stercorarius skua), Little gull (Hydrocoloeus minutus sny. Larus minutus,)	Yellow-legged gull (Larus michahellis) (14), Black tern (Chlidonias niger) (15), Little tern (Sternula albifrons) (26), Whiskered tern (Chlidonias hybrida) (36), Gull-billed tern (Gelechelidon nilotica) (47)	**Whiskered tern (Chlidonias hybrida)** (3), Gull-billed tern (Gelochelidon nilotica) (27), Yellow-legged gull (Larus michahellis) (32), Black-headed gull (Larus ridibundus) (34),	Lesser black-backed gull (Larus fuscus) (122)	

			backed gull (Larus fuscus), Black-legged kittiwake (Rissa tridactyla), Atlatic puffin (Fratercula arctica)	Black-headed gull (Chroicocephalus ridibundus), Mediterranean gull (Larus melanocephalus), Common gull (Larus canus), Great black-backed gull (Larus marinus), Yellow-legged gull (Larus michahellis), Common tern (Sterna hirundo), Arctic tern (Sterna paradisaea), Little tern (Sternula albifrons), Sandwich tern (Thalasseus sandvicensis), Caspian tern (Hydroprogne caspia), Common guillemot (Irua aalge), Razor-billed auk (Alca tora), Black guillemot (Cepphus grylle),				
Phoenicopteriformes	Flamingos				Greater flamingo (Phoenicopterus roseus) (20)		N/A	
Ciconiiformes	Storks		White stork (Ciconia ciconia), Black stork (Ciconia nigra)		Black stork (Ciconia nigra) (39)	Black stock (Ciconia nigra) (39)	White stork (Ciconia ciconia) (5361), Black stork (Ciconia nigra) (11)	
Podicipediformes	Grebes	Horned grebe (Podiceps auritus)	Red-necked grebe (Podiceps grisegena), Black-necked grebe Podiceps	Great crested grebe (Podiceps cristatus), Little grebe (Tachybaptus ruficollis), Black-				

			nigricollis) - Horned grebe (Podiceps auritus),	necked grebe (Podiceps nigricollis)				
Otidiformes	Bustards	Great bustard (Otis tarda)			**Great bustard (Otis tarda)** (4), **Little bustard (Tetrax terax)** (42)	**Great bustard (Otis tarda)** (6), **Little bustard (Tetrax terax)** (50)	**Little bustard (Tetrax tetrax)** (60)	Little bustard (Tetrax tetrax) (303), Eastern great bustard (Otis tarda dybowskii) (35), Western great bustard (Otis tarda tarda) (392), African houbara (Chlamydotis undulata) (197), Asian houbara (Chlamydotis macqueenii) (21), Ludwig's bustard (Neotis ludwigii) (1,538), Denham's bustard (Neotis denhami) (18), Kori bustard (Ardeotis kori) (121), Great indian bustard (Ardeotis nigriceps) (11) Bengal florican (Houbaropsis bengalensis) (6), Lesser florican

								(Sypheotides indicus) (5), Karoo bustard (Heterotetrax vigorsii) (66), Southern black bustard (Afrotis afra) (4), Northern black bustard (Afrotis afraoides) (49), Blue bustard (Eupodotis caerulescens) (9)
Gaviiformes	Divers	White-billed diver (Gavia adamsii)	Red-throated diver (Gavia stellata), Great northern diver (Gavia immer), Black-throated diver (Gavia arctica					
Suliformes	Gannets, cormorants Frigatebirds, anhingas, and boobies		Northern gannet (Morus bassanus)		Great cormorant (Phalacrocorax carbo) (16)			

Accipitriformes	Hawks, eagles, vultures, harriers	Lesser spotted eagle (Clanga pomarina), Golden eagle (Aquila chrysaetos)	Osprey (Pandion haliaetus), Greater spotted eagle (Aquila clanga), Hen harrier (Circus cyaneus) - Lesser spotted eagle (Clanga pomarina), Short-toed snake eagle (Carcaetus gallicus)	Montagu's harrier (Circus pygargus), Eurasian marsh harrier (Circus aeruginosus), Eurasian hobby (Falco Subbuteo), European honey buzzard (Pernis apivorus) - Golden eagle (Aquila chrysaetos), White-tailed eagle (Haliaeetus albicilla), Osprey (Pandion haliaetus), Hen harrier (Circus cyaneus), Red kite (Milvus milvus), Rough-legged buzzard (Buteo lagopus), Red-footed falcon (Falco vespertinus)	Osprey (Pandion haliaetus) (1), Bearded vulture (Gypaetus barbatus) (2), Egyptian Vulture (Neophron percnopterus) (5), Bonelli´s eagle (Aquila fasciata) (9), Spanish imperial eagle (Aquila adalberti) (17), Red kite (Milvus milvus) (19), Eurasian griffon vulture (Gyps fulvus) (25), Cinereous vulture (Aegypius monachus) (29), Montagu´s harrier (Circus pygargus) (46)	Egyptian vulture (Neophron percnopterus) (2), Bonelli's eagle (Aquila fasciata) (10), Hen harrier (Circus cyaneus) (14), Cinerous vulture (Aegypius monachus) (15), **Red kite (Milvus milvus)** (16), **Golden eagle (Aquila chrysaetos)** (17), **Spanish imperail eagle (Aquila adalberti)** (18), Eurasian goshawk (Accipiter gentilis) (22), Eurasian griffon vulture (Gyps fulvus) (24), Western marsh harrier (Circus aeruginosus) (28) Montagu's harrier (Circus pygargus) (33), **Short-toed snake eagle (Circaetus gallicus)** (40), Honey buzzard (Pernis apivorus) (42)	**Spanish imperial eagle (Aquila adalberti)** (270), Rough-legged buzzard (Buteo lagopus) (88), Long-legged buzzard (Buteo rufinus) (8), Hybrid spotted eagle (127), Griffon vulture (Gyps fulvus) (71), Egyptian vulture (Neophron percnopterus) (81), **Osprey (Pandion hallaetus)** (48), Honey buzzard (Pernis apivorus) (440), **Short-toed snake eagle (Circaetus gallicus)** (0), Western marsh harrier (Circus aeruginosus) (1), Montagu's harrier (Circus pygargus) (0)	
Falconiformes	Falcons						Peregrine falcon (Falco peregrinus) (0)	

Columbiformes	Pigeons and doves			Woodpigeon (Columba palumbus), Eurasian turtle dove (Streptopelia turtur)				
Strigiformes	Owls			Eurasian eagle owl (Buho buho), Ural owl (Strix uralensis), Little owl (Athene noctua), Eurasian scops owl (Otus scops), Short-eared owl (Asio flammeus)			Eurasian eagle owl (Buho buho) (6), Barn owl (Tyto alba) (0)	
Galliformes	Landfowl: Grouse, pheasants, quail, partridges	Black grouse (Lyrurus tetrix syn. Tetrao tetrix), Western capercaillie (Tetrao urogallus)	Ptarmigan (Lagopus muta)	Hazel grouse (Tetrastes bonasia), Rock partridge (Alectoris graeca), Grey partridge (Perdix perdix), European quail (Coturnix coturnix)	Western capercaillie (Tetrao urogallus) (13), Rock ptarmigan (Lagopus muta) (41), Grey partridge (Coturnix coturnix) (50), Black-bellied sandgrouse (Pterocles orientalis) (28), Pin-tailed sandgrouse (Pterocles alchata) (35)	Pin-tailed sangrouse (Pterocles alchata) (7), Black-bellied sandgrouse (Pterocles orientalis) (30),		
Piciformes	Woodpeckers			Eurasian wryneck (Jynx torquilla), White-backed woodpecker (Dendrocopos leucotos),				

Passeriformes	Song birds, corvids			Ring ouzel (Turdus torquatus), Common starling (Sturnus vulgaris), Common raven (Corvus corax), Alpine chough (Pyrrhocorax graculus), Great grey shrike (Lanius excubitor), Woodchat shrike (Lanius senator), Eurasian penduline tit (Remiz pendulinus), Crested lark (Galerida cristata), Aquatic warbler (Acrocephalus paludicola), Barred warbler (Curruca nisoria), Wallcreeper (Tichodroma muraria), Common rock thrush (Monticola saxatilis), European whinchat (Saxicola rubetra), Eurasian wheatear (Oenanthe oenanthe), White-winged snowfinch (Montifringilla nivalis), Tawny pipit (Anthus campestris), Meadow pipit (Anthus pratensis), Common rosefinch (Carpodacus erythrinus), European citril finch (Carduelis citrinella), Eurasian	Lesser grey shrike (10), Dupont's lark (22), Common reed bunting (23), Rufous-tailed scrub robin (24), Rook (30), Moustached warbler (33)	Red-billed chough (Pyrrhocorax pyrrhocorax) (1), Black wheatear Oenanthe leucura) (12), Mediterranean short-toed lark (Alaudala rufescens syn. Calandrella rufescens) (21), Water pipit (Anthus spinoletta) (29), Common rock thrush (Monticola saxatilis) (35), Common reed runting (Common reed bunting) (46), Savi's warbler (Locustella luscinioides) (48)		

				rock bunting (Emberiza cia), Ortolan (Emberiza hortulana) - Lesser grey shrike (Lanius minor), Water ouzel (Cinclus cinclus),				
Others	Nighjars, swifts, hoopoe, fulmars, rollers			European nightjar (Camprimulgus europaeus), Alpine swift (Tachymarptis melba), Eurasian hoopoe (Upupa epops), Northern fulmar (Fulmarus glacialis) - Leach's storm petrel (Hydrobates leucorhous), Sooty shearwater (Ardenna grisea), European roller (Coracias garrulus),				

Chapter 4
External Factors Influencing Bird Collision

Power lines of various dimensions and voltage levels are found in diverse geographical contexts, habitat types and climate types across the world. It is thus inevitable that any given power line project will be subject to a complex (shifting) constellation of factors which in turn influence the level of risk for collision of birds. Before further detailing the multitude of extrinsic factors at play in, it is essential to understand that these elements are interrelated, and together, they significantly impact the probability of collision incidents.

The external factors which impact the collision risk of power line in a given site can be broken down into:

> **1) Site-specific factors:** such as topography, habitat features (e.g. vegetation), weather and light conditions and human disturbance (e.g. hunting, transportation, power line maintenance).
> **2) Power line-specific factors**: such as number of vertical phase conductors, conductor height, conductor diameter and presence of an earth wire.

The following points have been adapted from Bernadino et al.'s 2018 meta-study, wherein many more references can be found.

4.1 Site-Specific Factors

Topography

The land formations in a given area play an important role in informing the direction and height at which birds fly and thus the likelihood for them to come into contact with power lines. Landforms such as coastlines, river valleys, mountain passes and ridges channel and concentrate flight paths and, in many cases, high levels of mortality is reported in such areas (Bevanger, 1994; Haas et al., 2005). For example, shorebirds often gather and fly along coastlines, while mountain chains provide thermals and updraught which benefit the flight of migratory species. Recognising these geographically sensitive zones and considering avoiding in route planning or prioritising mitigation measures in these areas can be pivotal to avoid and reduce collision risk. Any topographical feature that concentrates migratory flocks into a narrow channel should be given priority treatment either at planning stage or mitigation planning.

Habitat

Collision risk is highest when power lines are located close to areas from which birds take off or land. Open areas like swamps and pastures allow birds to fly at lower altitudes, increasing the risk of collisions with power lines in these areas. In forested regions, certain birds fly just above the tree canopy, and collisions are more likely when power lines just exceed the height of nearby trees, thus obliging birds to increase their flight height (Prinsen et al., 2011; Bernadino et al., 2018). High-risk areas for bird collisions include wetlands, coastlines, and major bird congregation sites (e.g. wetlands) during migration. Additionally, consideration should be given to areas such as riverbanks and landfills which are heavily frequented by various bird species.

As discussed on page 25, Integrated Vegetation Management (IVM) is a method by which grid operators can restore ecosystems around power lines, whilst removing vegetation which could pose a problem to security of supply. The potential of IVM in terms of supporting biodiversity is promising, however the risk of attracting more birds to restored areas should be countered by measures such as wire markers.

Weather and light conditions

Adverse weather conditions significantly affect bird flight behaviour and their ability to detect power lines, leading to increased collision risks. Fog, rain, snow, and low cloud ceilings force birds to fly at lower altitudes, increasing the likelihood of collisions. Indeed, most reported incidents of mass bird mortality with anthropogenic structures have occurred during such weather conditions" (Bernadino et al., 2018:5). Wind speed and direction also play a role, as strong tail and crosswinds can accelerate bird flight and reduce their control near power lines, while headwinds force birds to fly lower to conserve energy, potentially increasing collision risk. Light conditions are another important factor, especially in high-latitude regions with varying daylight hours. Poor light during winter and early spring has been linked to higher collision risks, especially for nocturnal waterbirds, which may react less effectively to power lines in darkness, increasing the risk of collisions during night-time conditions.

Anthropogenic disturbance

Bird collisions with power lines can result following human-induced disturbances. There are many sources of disturbance: line construction and maintenance, in addition to recreational activities (hunting, fishing, hiking), agricultural activities, and transportation (cars, trains and planes).

Furthermore, transportation-related disturbances caused by roads, railways, and aircraft noise may elevate collision risks near power lines. While some research suggests that the presence of motorways can increase the likelihood of bird collisions, other studies propose that birds may actively avoid areas with high human activity, potentially reducing collision risk (Shaw et al., 2018; Silva et al., 2010). To gain a deeper understanding of these relationships between human activities and bird collisions with nearby power lines, further investigation and research are required.

4.2 Power Line-Specific Factors

Avian collisions occur on all overhead lines, power distribution, power transmission, railway, and on communication lines. Key power line characteristics that can impact the risk of bird collisions include conductor diameter, height above the ground, and line configuration, specifically the number of vertical conductor levels. The collision risk is elevated on:

- Taller structures.
- Longer spans.
- When smaller diameter conductors or ground wires are used.
- On circuit designs that arrange the phase conductors vertically.

It is important to note that collision risk is not directly linked with voltage level – that is to say, neither transmission nor distribution lines are by nature more dangerous than the other. Instead, the level of risk depends on technical and spatial characteristics of the power lines themselves, such as height, size of pylons, number of conductors, bundling of wires, presence of a ground wire etc., as well as siting of the wire close to high-risk areas. That said, these factors are indeed dictated to the relatively rigid technical constraints of grid design at the different voltage levels, linked to engineering performance, service reliability, public safety and cost-driven decisions made by electricity companies, national governments, and regulatory bodies (Bernadino et al., 2018).

Conductor height (Horizontal vs. vertical structures)

Globally, most distribution structures arrange the three conductor phases horizontally. However, at transmission voltages, it is not uncommon to see vertical arrangement of the phase conductors. This design is often implemented when lines are upgraded within fixed grid corridors.

There are two reasons driving this:

- Line capacity or system voltage upgrade, requiring higher phase to phase clearances, (attainable in the vertical direction, but not safely attainable horizontally within the fixed corridor).
- Merging of two circuits on one tower, resulting in 6 (or more) conductors and ground wire on one tower.

As discussed in Bernadino et al. (2018), it makes intuitive sense that the number of wire levels and the spacing between them has an impact on the risk of bird collision. However, the practical challenge of testing this thesis means that scientific evidence in this regard is limited. Despite this, several studies suggest that reducing the number of vertical levels can lead to lower collision rates (e.g., Bevanger & Brøseth, 2001; APLIC, 2012; Prinsen et al., 2011).

Structure, conductor and ground wire heights

According to Gauld et al. (2022), most of the overhead distribution and transmission lines are in the height range 10-60m. Birds passing the lines at these altitudes are at risk of collision, whether when flying past or during a take-off or landing flight.
Conductor height plays a role in collision risk, with taller vertical circuit structures generally posing higher risks because:

- Structure of vertical phase conductors plus one ground wire presents risk at four different altitudes.
- Birds tend to try to gain altitude to fly over the top of power lines rather than pass below, and therefore risk hitting the less visible, (smaller diameter) ground wire.
- Transmission lines tend to be taller, and the spans longer therefore the mid span is further away from the big structures, reducing the overall visibility of the line.
- Distribution lines have more structures, meaning they are more dangerous from an electrocution point of view, but shorter spans mean more poles and lower 'kill zone' length per kilometre.

Few studies have directly examined the influence of wire height alone on collision incidence. Similarly, there are conflicting views in the literature on whether there are more collisions on transmission lines or distribution lines. Some authors have compared collision rates between distribution and transmission lines and produced results which suggest that transmission lines are associated with higher collision rates than distribution lines (Infante et al., 2005; Manville, 2005; Shaw et al., 2018). However, this is not universally true, as demonstrated for example by a recent study in Norway which found that the impact of bird collisions was more severe on the distribution grid than on transmission lines (Gilad et al., 2024). What is certain is that collisions can and do indeed occur with all lines, and the location of the lines has a strong influence on collision risk.

Importantly, wire height is also dictated by the voltage level and as such is closely linked to other factors such as number of wires, spacing of wire length, span length, and cable diameter of conductors compared to the earth wire.

Conductor diameter & presence of 'ground wire'

The purpose of a ground wire is to prevent damage to the conductor cables in case of a lightning strike. There are two factors affecting the visibility of the ground wire:

- Ground wires are usually deployed on taller transmission lines, which typically have longer spans between towers. These larger distances between the midspan point and the adjacent tower structures reduces the visual impact of the towers, increasing the collision risk.
- Ground wires are typically produced with smaller diameters, making the wire less visible than larger single or bundles phase conductors underneath.

Given the direct link between the diameter of a wire and its visibility, this factor is widely understood to be a determinant of collision risk (e.g. Jenkins et al., 2010). Ground wires are considerably thinner than current-carrying wires and are often placed alone (or in pairs) above the conductor wires (which, conversely, are often bundled). Thus, birds may try to avoid phase conductors by flying over them, only to collide with ground wires. Indeed, most reported collisions on transmission lines involve ground wires (Dwyer et al., 2022), as confirmed in Bernadino et al.'s 2018 meta-study, of a total 208 collisions from across five studies, 84% involved ground wires, and 16% involved conductors.

Chapter 5

Basic Principles for Effective Wire Markers

Research confirms that wire marking can indeed present an effective method to reduce bird collision with power lines (Jenkins et al., 2010; Williams et al., 2018; APLIC, 2018; Bernadino et al., 2019). Clearly though, the multitude of factors at play in determining the level of risk mean that not just any marker will suffice to be effective in reducing collisions.

A highly effective marker should take account of the bird-specific factors determining sensitivity (due to their behaviour, morphology and sensory ecology), as well as the environmental factors (such as weather and light conditions) and site-specific factors (topography, habitat). On page 4 of the Brochure, we summarise scientific insights on basic principles for effective wire markers.

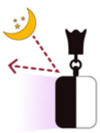
Considering that it is unlikely for any one marker to be equally as effective for all species, Martin (2022) suggests taking the 'worst-case species' example of the Canada goose (*Branta canadensis)* – being particularly susceptible to collisions on account of morphological and behavioural factors (see also pg. 27) to be the basis of wire marker design and deployment. In this context, the basic requirement is that the marker should be detectable by a goose flying at a typical speed around twilight from a sufficient distance so that the bird can avoid collision by changing course.

From the grid operator perspective, practical usability and safety are key. Wire markers must be designed in consideration of the technical and regulatory requirements and restrictions in place (including budget, safety, material requirements).

In summary, an effective and useable wire marker should:

- Effectively reduce collision for many species by increasing visibility at any time of the day, year-round in diverse weather and light conditions.
- Be based on the vision of birds (rather than humans) and be effective for a 'worse-case species' (to be more likely to be effective for a broad range of sensitive bird species).
- Fit the requirements of safe and cost-effective installation and grid operation over a long period of time.

Drawing from both extensive research and practical experience, below we present a compilation of essential principles for an effective marker.



High visibility in low-light and internal contrast

In terms of visibility, contrast against the environmental background and internal contrast (within the marker itself) are the key points to consider. Considering the range of background conditions against which a flight obstacle appears under natural conditions (i.e. changes in brightness and colour of clouds, light levels, vegetation and landscape), an effective marker must have a high level of internal contrast to be visible in all conditions, including low light or decreased visibility caused by rain or mist (NABU, 2013). The 'Michelson Contrast' is a simple measure using a simple ratio based on the luminance of dark and bright sections of a surface.

A simple high-contrast pattern of black and white is understood to be the most detectable throughout the full range of naturally occurring light levels (Martin 2017; 2022). While bright colours may seem to be an attractive option here, chromatic (colourful) patterns are only visible in higher light levels –appearing in grey shades at low light levels - (Land & Nilsson, 2012), and their spatial resolution (ability to be distinguished) is always lower than achromatic (non-colourful) patterns (Lind & Kelber, 2011; Potiert et al., 2018 in Martin 2022). For maximum contrast, black sections should be highly absorbing and white sections should be highly reflective (Martin, 2022).

A phosphorescent or 'glow-in-the-dark' coating to some materials could be beneficial to increase visibility in low light (NABU & RPS, 2021). Moreover, considering that around half of all bird species (including passerines and gulls), have UV-sensitive vision, beaming UV-light onto power lines could be effective in reducing avian collisions, particularly during nighttime conditions, and has shown enhanced efficacy when combined with existing BFDs (Martin, 2017; Baasch et al., 2022). However, it should be noted that not all birds possess the ability to perceive UV light. A novel accompaniment to power line marking involves the utilisation of ultraviolet (UV) light to illuminate the power lines and any markers present for greater wire visibility in low light and darkness. This is especially relevant in narrower power line corridors, where the reaction time available to birds is lower. One study on two 260m power lines fitted with wire markers, found that UV illumination using the Avian Collision Avoidance System (ACAS) reduced collisions by 88% (Baasch et al., 2022). Another study found a 98% collision reduction for Sandhill cranes (Antigone canadensis) (Dywer et al., 2019). However, research is still preliminary, and more studies are required. Furthermore, the potential for UV illumination to attract insects and thus nocturnal foragers such as bars and caprimulgiform birds (e.g. nightjars) should be further investigated.

In general, more research into the visibility of different colour combinations for bird species is recommended.

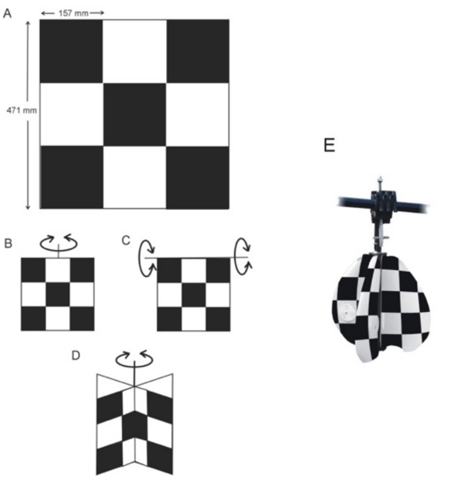
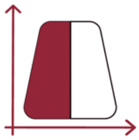


Figure 13. Martin (2022) Design elements of a 'worst-case' bird diverter based upon the vision of a Canada Goose. (B–D), depicts possible ways that the checkerboard pattern could be made to oscillate or rotate. The dimensions given in A indicate the physical size that should ensure a flying Canada Goose would be able to detect the diverter at a sufficient distance to change its flight trajectory and avoid the obstacle. (E), a possible interpretation of how the design features could be combined in a device.



Sufficiently large

The size of bird deterrents must meet specific criteria, taking into consideration bird acuity, which encompasses their field of view, visual sharpness, detection from distance and in movement (Martin, 2017). These characteristics greatly enhance the likelihood of a stimulus being recognised from a distance significant enough to trigger a change in the bird's flight path.

As a rule of thumb, larger a marker, the more likely it is to be visible to birds (provided it fulfils criteria such as contrast, mobility etc.), however it should be small enough to be able to be safely applied at regular distances across the line, i.e. its size and mass should not be so great so that repeated application would apply too much weight to the power line (Martin, 2022). Martin (2022) suggests a 471x471mm square, consisting of a 3x3 checkerboard pattern of 157mm squares (ibid.).

Movement

Motion is an effective mechanism for enhancing the visibility of a device though spinning, swinging or flicker in the presence of wind or vibration. It is important to ensure that the device has the capability to rotate or flap freely, especially at night, to more effectively draw the attention of birds (NABU, 2013; Liesenjohann et al, 2019; Martin 2022). The factors of contrast and mobility can be combined to give an even higher visibility, if a high contrast oscillating pattern or checkerboard design is used to combine black and white alternatively within. The movement should be powered by the wind (as opposed to a motor, which may bring additional need for maintenance) and should move with little resistant.

It should be noted, that in the lightest of winds will cause conductors and ground wires to sway or vibrate. In these circumstances, even fixed wire markers with prismatic reflective surfaces will flicker in the sun (or moon)light. On the rare day where there is no wind, neither the dynamic or fixed devices will move, nor will they offer flicker reflection.

Durable over time and under different weather conditions

Enhancing the longevity of bird markers is vital for maintaining their effectiveness and functionality over extended periods, especially under diverse weather conditions. This not only ensures sustained efficiency in their purpose but also reduces the need for frequent maintenance. Several grid operators have noted that an ideal marker would be able to demonstrate a useable lifespan of at least as long in time as that of the infrastructure itself, thus around 20 years. The short life span of some markers has been cited as a major factor in some grid operators' solution selection and in the decision whether to use a wire marker in the first place.

Each manufacturer should specify the maximum working wind loading that their design should be installed in and this should be tested following a suitably recognised test method.

A durable design should be mechanically sound and produced from materials that are all capable of enduring the installation environment for the lifetime expectancy of the device. The polymeric materials should be resistant to:

- UV radiation.
- A specific min/max temperature range, considering the thermal stresses of the conductor and the environment.
- Electrical and mechanical stresses.
- Resistant to local pollutants (site specific examples are coastal salt, road salt, industrial pollutants).
- All metal components should be corrosion-resistant and of suitable strength for the application range.

The product design tests should evaluate the performance of:

- Moving parts, defined by suitable cyclical testing.
- Stability of the visual indication surfaces over time (e.g. prismatic, fluorescing, phosphorescent).
- Electrical testing corona, radio influence voltage (RIV) limits.
- Maximum wind service loading recommendations with an evaluation line fixing mechanism (i.e. clamp) and the moving parts.[23] Grid operators in highly windy areas are advised to pay particular attention to this consideration.
- Aeolian vibration (for larger and heavier devices).

Anecdotal evidence from grid operators suggests that early designs of wire markers suffered the following mechanical issues:

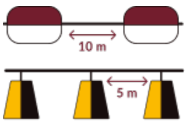
- Mechanism failures, e.g. wire markers moved along line.
- UV degradation, e.g. colour change, embrittlement of rubber components and flapper.
- Failure of metal components supporting mobile flappers.
- Rotation of the device on the conductor or ground wire.

[23] Bernadino et al. (2019) cites evidence that flappers particularly exposed to wind may lose their functionality faster than static devices (Dashnyam et al., 2016), which compromises long-term effectiveness and entails additional costs with device replacement (Lobermeier et al., 2015).

Economically feasible

A highly expensive wire marker will be a considerable burden for grid operators and thus more difficult to integrated into standard operational budgets. The annualised lifetime cost of a marker pertains to the unit cost plus the installation cost per unit, divided by its serviceable life in years. A marker is therefore 'economically feasible' if it can be reasonably integrated into grid operator budgets in terms of cost per unit, cost of installation and total lifetime costs.

Currently available installation methods include ground bucket truck, boat, helicopter, hot stick or drone (NABU & RPS, 2021). Currently, many wire markers on ground wires are installed using helicopters, as it is unsafe to reach from the ground past conductors to the wires above. The use of helicopters brings challenges regarding safety, logistics and cost, which may be difficult for grid operators to accommodate (Baasch et al., 2019). The use of unmanned aircraft systems (i.e. drones) provides a promising alternative to helicopter deployment (read more in chapter 6). An important distinction should be made for markers which can be installed onto energised power lines, or if the power line must be switched off – the latter being more costly and logistically difficult.



Ability to be mounted in regular intervals

The smaller the gap between markers, the higher the chance is of several devices coming into the field of view of an oncoming bird. Research and practical insights suggest they are most effective when mounted at shorter intervals. Recommendations on interval size here vary, from 5-10m up to a maximum of 15-20m (NABU, 2013; BirdLife International, 2022). However, generalising this approach can be challenging. For example, a 5m spacing is recommended for markers on single conductors, but this varies for some manufacturers.

Therefore, the rule of thumb is to place them as closely together on the same wire as engineering constraints permit (Martin, 2022). This recommendation aligns with studies assessing the effectiveness of bird markers at varying interval spacings (Liesenjohann et al., 2019; Silva et al., 2023).

Chapter 6
Practice and Research on Effectiveness of Wire Markers

Wire marking to enhance the visibility of power lines for birds has become the preferred mitigation solution to reduce collisions. In response, several companies have developed wire markers now in use by grid operators worldwide. Combined with varying regulatory frameworks and guidance (e.g. regarding technical/material requirements) and a lack of consensus regarding the effectiveness of different models, approaches to wire marking vary widely between countries and even between grid operators within the same country. This chapter will explore these approaches, available products and key factors which grid operators might consider when selecting appropriate wire marker.

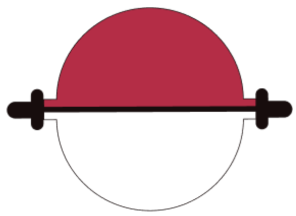
For an overview of the wire markers currently available on the market, see:

- Scientias-Energy (2024). Preventing Avian Collisions: A global best practice & buyers guide
- Avian Power Line Interaction Committee (APLIC) (2012). Reducing Avian Collisions with Power Lines: The State of the Art in 2012.
- NABU & RPS (2021). Electrocutions & Collisions of Birds in EU Countries: The Negative Impact & Best Practices for Mitigation
- Dywer et al./IUCN (2022). Chapter 4: Collision. Wildlife and power lines. Guidelines for preventing and mitigating wildlife mortality associated with electricity distribution networks. IUCN. pp.60-83.

6.1 An Introduction to Wire Markers

Wire markers can be broadly categorised into three types of devices:

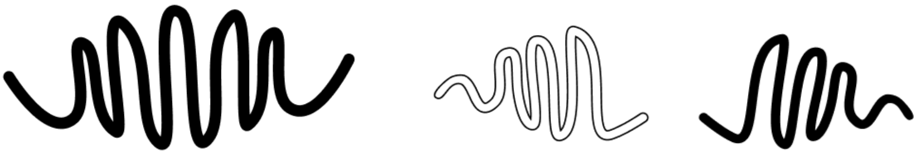
Large spheres (static)



These spheres range in diameter from 130-140cm and are akin to the aviation balls used to warn aircraft of the presence of power lines. There are various models available, including one where half of the ball is fluorescent. Maximum application voltage varies with manufacturer, but they can typically be used up to 110kV on phase conductors and on ground wire subject to weight check. Grid operators should consult with manufacturers regarding voltage level and weight implications.

Spirals (static)

Passive (immobile) spirals, generally made from PVC. Available in a variety of sizes and colours. Can be applied on conductors up to 230kV and on ground wires. Two different models in circulation are the large symmetrical spiral and smaller 'pigtail' spiral.



Suspended devices or 'flappers' (dynamic - swinging, rotating and fixed)

Active (mobile) polymeric/composite shapes which hang from a composite clamp attached to a power line. Typically used on ground wires, however some types of flappers may be used on phase conductors up to 69kV. The size, colours, mounting method, type of motion and application voltages varies by manufacturer.

6.2 Cost and Installation of Wire Markers

The extent to which grid operators can undertake wire marking is often limited by the available budget. In general, retroactive installation of wire markers on existing power lines is considered an operating expense (OPEX), whereas installation during the construction of new lines is considered part of the overall investment and therefore a capital expense (CAPEX).

When selecting the wire marker for a specific power line span, grid operators must take into consideration the total cost of the installation. The cost per unit of the marker itself is generally a less influential factor than the cost and logistics involved in the installation process. Indeed, different wire marker devices require different installation techniques, including by helicopter, ground bucket truck, hot stick, adapted line 'bicycles', boat or drone (i.e. unmanned-avian vehicle, UAV). Each method may imply the deployment of trained staff, use of specialised installation equipment and, in cases where markers cannot be installed onto energised power lines, scheduling a shutdown for the affecting section, which can be logistically challenging.

Other important factors which can influence the use of wire markers include line design, voltage level, location in the terrain, negotiation with landowners/users, weather, duration of installation and health and safety considerations (for example when technicians climbing onto the power line using 'bicycles') (NABU & RPS, 2021). It can be advantageous in terms of budget and logistics for grid operators to already install wire markers when the power lines are being erected, or indeed to align installation with other planned maintenance works which may require a line to be de-energised or a helicopter to be deployed. While it is possible to install most designs of wire markers under live working conditions, this is subject to the grid operators risk assessment, following local regulations and company specific work practices.

6.3 Emerging Technologies

There are currently a range of innovations being advanced which bring considerably potential to further benefit the efficiency of wire marker installation, collision prevention, and mortality monitoring. These include automation in installation (e.g. drones, robots), collision sensors, sound and light.

Automation in wire marker installation

According to Brian McGowan of Scientias-Energy, "The use of drones and robots in wire marker installation is an industry game changer. Drone installations significantly reduce the total cost of installation per diverter, while eliminating enormous safety concerns associated with live line working".

Drones can enable safer, more efficient and lower cost marker installation in the most difficult terrains over water and in mountainous regions. They can facilitate the installation of around 300 devices per day, and more in optimal conditions. Robotics have also improved the speed, accuracy of spacing and quality of the installation on live conductors.
Drones eliminate dangerous human and helicopter interaction with live lines which is a significant consideration for utilities. Activities involving drones are subject to regulation, and their use must always be cleared with a relevant national aviation regulatory authority.

The industry is still working to reduce the limitations of drone automation related to battery life, shipping constraints of lithium batteries, performance in wind and rain and the operating range which would further enhance their efficiency.

Figure 14. Automated wire marker installation methods. Source Raptor Protection Slovakia

Ultraviolet light as a bird collision prevention

Several manufacturers are exploring the use of UV light beams to illuminate lines in low light conditions and at night, often in connection with existing markers to enhance their visibility.

While still emerging, experiments have shown promising results, such as research by Dywer at al. (2019) and Baasch et al. (2022) on the Avian Collision Avoidance System (ACAS), which demonstrated collision reduction by 98% and 88%, respectively. The potential for UV illumination to attract insects, and thus nocturnal foragers such as bats and caprimulgiform birds (e.g. nightjars) require further investigation. In the context of the LIFE-SafeLines4Birds project, ACAS will be deployed at two sites in France and Belgium, with documented bird collisions and monitored by experts from civil society[24].

See chapter 5 for more information on this approach and summarised studies in the research overview table at the end of this chapter.

Figure 15. An illustration of the Avian Collision Avoidance System (ACAS) being shone onto power lines where markers are present. Source EDM International (2024).

Vibration sensors to monitor bird collisions

Vibration sensors have been successfully used to count ad locate collisions on long spans of overhead lines, helping to increase collision studies. In a 2016 study in Nebraska, USA, sensors known as 'Bird Strike Indicators'[25] were used to detect collision-related mortality of sandhill cranes *(Antigone canadensis)* and found that >95% of collisions occurred during the night.

6.4 Research on Wire Marker Effectiveness

There is a general lack of uniformity in grid operators' approaches to choosing and localising wire markers. This fractured landscape in practice is mirrored in a lack of uniformity regarding scientific assessment of the effectiveness of wire markers. On the one hand, the multitude of external factors which determine risk level – including bird-specific, power line-specific, and

[24] More information on the project and – in the future – project results will be available on the webpage.
[25] The *Bird Strike Indicator* (BSI) is an impulse-based vibration sensing and recording tool to detect bird strikes on aerial cables. For more information, see Harness et al., 2003 and visit the website of the developer, EDM Link.

environmental factors - impede a linear comparison between the results effectiveness studies in different contexts. On the other hand, diversity in methodological approaches to monitoring preclude a standard scientific comparison of results regarding reduction in collision figures (see 1.5 and 1.6 for a discussion and further references).

The studies we encountered varied as to the design of the data gathering process, either Control-Impact (CI), Before-After (BA) or Before-After-Control-Impact (BACI). The BACI design is generally considered to be a more robust methodology as it accounts for differences between treatment and control groups, which – if not accounted for – can affect the reliability of conclusions (Bernadino et al., 2019; Christie et al., 2019). In the case at hand, such spatio-temporal variations could include differences in mortality rates between survey areas caused by factors other than wire marking, such as differences in bird abundance or carcass removal rates by scavengers (Bernadino et al., 2019).

Thus, as summarised in section 1.5. on 'Methodology', when reviewing the available research on the effectiveness of different markers, we were obliged to set some 'rules' to bring a level of scientific objectivity to the activity. Following the guidance of expert scientists, we decided on the following rules:

- We refrained from calculating novel averages between different studies into marker effectiveness, and instead clearly present the effectiveness scores calculated from individual studies' data sets.
- The methodology of the studies into the effectiveness of the markers should always be described and clearly marked for readers' attention.
- The **Methodology Report** would include a **Study Summary Table** of all available studies seeking to quantify effectiveness of wire markers, regardless of their methodology.
- The **Brochure** would include an overview of studies for which we a minimum of four scientifically rigorous studies were available (according to Bernadino et al., 2019).
- We prioritised BACI-designed studies which were able to provide an effectiveness score (%) in terms of the reduction in collision incidents after wire marker installation compared to the before and control periods.
- Noting that there were too few BACI studies available to facilitate an interesting collocation of marker research, we would also include in the **Brochure** BA / CI-design studies, on the condition that they had been subject to a peer-review process and clearly presented their methodology.
    - NB: For some studies, the effectiveness scores cited in the narrative text of the 'Results' or 'Conclusion' section differs from the actual data provided. Where this was the case, we worked closely with an expert researcher to calculate the true effectiveness score according to actual collision reduces as per BACI methodology. These figures were corroborated with the study's authors.
- Studies which followed these methodologies but were unable to confidently provide an effectiveness score would not be included in the **Brochure,** and instead included in the **Study Summary Table**.
- Studies which combined the effectiveness of more than one marker were not included in the brochure overview, and instead described fully in the **Study Summary Table.**

After reviewing the research, we found one marker from each of the following categories for which a minimum of 4 BACI / or peer-reviewed BA/CI effectiveness studies had been carried out:

- Small dynamic flapper: Firefly (HAMMAR) *(Top Left)*
- Large dynamic flapper: 'Zebra' marker (RIBE) *(Top Right)*
- Static small spiral: Swan Flight Diverter (PLP) *(Bottom Left)*
- Static large spiral: Bird Flight Diverter (PLP) *(Bottom Right)*

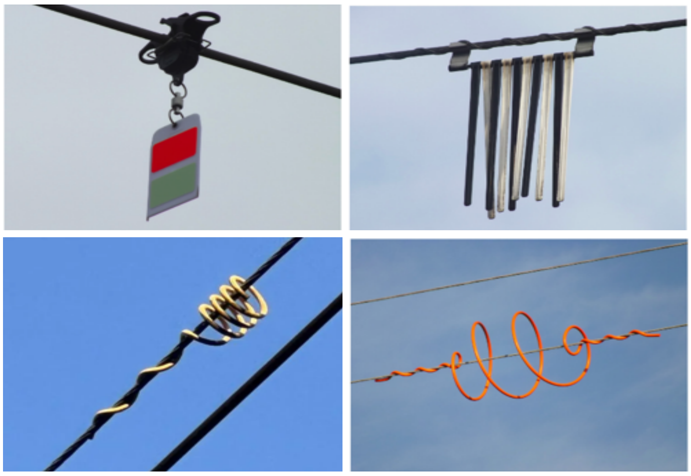


Figure 16. Wire markers for which a minimum of 4 BACI / or peer-reviewed BA/CI effectiveness studies were found. Adapted from RPS (2021).

On the next pages, we provide a summary of the above 4 markers in their respective 'category', including information such as mounting method, weight per unit, dimensions, luminescence and manoeuvrability. This data was sourced from manufacturers' catalogues or from manufacturers directly in the process of technical review of this report. For more information on the respective markers, readers can consult the respective catalogues of the individual products. A comprehensive overview of these factors and more relevant information for grid operators can be found in "Preventing Avian Collisions: A global best practice & buyers guide".

Information regarding the technical specifications of markers which were reviewed in other studies (but which did not fulfil the aforementioned conditions) can be found in the appropriate columns of the respective studies in **Study Summary Table**.

Table 6. An overview of wire markers on the market pertaining to each of the identified categories. Technical details are provided for the four markers for which a minimum for 4 BACI or peer-reviewed BA/CI studies could be found.

	DYNAMIC		**STATIC**		
	Small	**Large**	**Small - Spiral**	**Large - Spiral**	**Rigid designed**
Motion (when exposed to a breeze)	**Swinging, rotating**	**Swinging, rotating**	**No Motion**	**No Motion**	**No Motion, (can flicker, [note 1])**
Visible area (perpendicular to line - Horizontal cm sq)	<250 cm sq	>250 cm sq	Outer coil dimensions up to 12.7 cm x 38 cm (5 x 15 inches)	Outer coil dimensions up to 20 cm x 116 cm (8 x 46 inches)	<250 cm sq
Selection of other manufacturers	HAMMAR (Firefly, Birdmark)	RIBE (Zebra)	PLP (Bird Flight Diverter)	PLP (Swan Flight Diverter)	Sicame (Power Line Sentry Hawkeye)
	Carbon 2050 (Crocfast)	SAPREM (BAGTR, BAGTS)	Huaneng Telecom Limited	Huaneng Telecom Limited	HAMMAR (Static firefly)
	PLP (RAPTOR)	Pitch Aero (Feather Fender)			TE Connectivity
	Balmoral Engineering (Birdflappa)	Balmoral Engineering (Rotamarker)			
	SAPREM (rubber beacon)				
Examples for which 4 BACI or peer-reviewed BA/CI studies were found	HAMMAR FireFly	RIBE Zebra	PLP Bird Flight Diverter (3341)	PLP Swan Flight Diverter (1520)	No BACI papers; included for comparision purposes only - Sicame (Power Line Sentry Hawkeye 050)
Size (viewed from side vertical plane cm sq)	178 cm sq	1,536 cm sq	N/A	N/A	135 cm sq
Reflective surfaces (prismatic elements)	Yes	No	No	No	Yes
Luminescent surface Y/N (Afterglow in hours [note 2])	Yes (14hr)		No	No	Yes (24hr)
Motion (when exposed to a breeze)	Rotates and swings	Swings	No motion	No motion	No motion (can flicker [note 1])
Weight (grams)	210g	1,250g	N/A	630g	119g

Conductor range (diameter mm)	4 - 70mm	N/A	4.4-28mm	4-38mm	6-38mm
Max recommended system voltage	110kV on phase No limit on ground wire	N/A	230kV on phase conductor No limit on ground wire	230kV on phase conductor No limit on ground wire	345kV on phase conductor No limit on ground wire
Recommended spacing single conductor	5-10m	N/A	5m	5m	5-15m
Application temperature(degrees Celsius)	-20C to +100C	N/A	-20C to +60C	-20C to +60C	-40C to +100C
Wind testing (limits)	162km/hr for 15min	N/A	Manufacturer claims no maximum wind speed	Manufacturer claims no maximum wind speed	193km/hr for 5min
Manufacturer installation methods	Manual: Bucket truck, line bicycle, hotstick Helicopter Drone, robot	Manual: Bucket truck, line bicycle Helicopter	Manual: Bucket truck, line bicycle Helicopter Drone, robot	Manual: Bucket truck, line bicycle Helicopter	Manual: Bucket truck, line bicycle, hotstick Helicopter Drone, robot
Drone installation Qty/hr excluding set up: (based on manufacturers inputs)	300	N/A	320	N/A	400

Notes on Table:

1. Subtle movement associated with the movement of the combined line and diverter, can reflect light delivering a flickering effect.
2. Test methods used to establish the strength of afterglow vary between manufacturers.

Chapter 7

Further Documents

All further documents pertaining to this initaitive can be found on our website.

Brochure

The brochure gives an abridged, user-friendly overview on the topic and available research.

Study Summary Table

The Study Summary Table contains a review of 50 studies into the effectiveness of wire markers.

Annex I) Overview of Relevant German Studies on Wire Marker Effectiveness and Bird Susceptibility to Collision with Power Lines

This document provides a summary of relevant studies and guidelines from the German context on wire marker effectiveness and evaluation of bird susceptibility to power line collision, which were previously not (or only partially) available in English. Links to the original documents are provided.

Annex II) Similarity Index of Reference Species and Comparison Species Based on Liesenjohann et al. (2019)

This table shows 'reference species' which can be used to evaluate the susceptibility of 'comparison species' for which no research on collision risk susceptibility is available. It is based on 10 criteria and similarity-based CSR collision reduction values. See Annex I for an explanation of methodology. Translated from Liesenjohann et al. (2019).

Chapter 8
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