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METHODS ARTICLE

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# Between the lines

## Life cycle impact assessment models of collision and electrocution impacts of power lines on bird diversity in Norway

Dafna Gilad[1] | Roel May[2] | Bård G. Stokke[2] | Francesca Verones[1]

[1]Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

[2]Norwegian Institute for Nature Research (NINA), Trondheim, Norway

**Correspondence**
Dafna Gilad, Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.
Email: dafna.gilad@ntnu.no

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**Abstract**

The expansion of the electric grid is inevitable. Renewable energy is on the rise, and new transmission lines must be built to link new electricity production facilities with the local network. In addition, higher electricity demand due to electrification will lead to the growth of the distribution grid. However, further construction of power lines will affect the local biodiversity. Birds are especially vulnerable: every year, power lines cause the deaths of hundreds of millions of birds by collision and electrocution. Yet the environmental impacts of the electric grid in life cycle assessment (LCA) are limited to a few impact categories, failing to cover the area of protection for damages to ecosystem quality. We developed the first methodology to quantify power lines' collision and electrocution impacts on bird richness within LCA. We calculated the potentially disappeared fraction of species (PDF) by developing species–area relationships using high-resolution species distribution maps, species-specific characteristics, and the location of power lines and pylons. We applied our models to Norway, a country that aims to become a low-emission nation by 2050. The characterization factors ranged between $8.48 \times 10^{-16}$ and $5.6 \times 10^{-15}$ PDF*yr/kWh for collision and $3.27 \times 10^{-18}$ and $1.66 \times 10^{-16}$ PDF*yr/kWh for electrocution. Integrating power lines' impacts on biodiversity in LCA is essential, as harmonized models can estimate the effects of electricity production alongside the impacts of electricity distribution. This brings us a step further in promoting a holistic assessment of energy systems.

**KEYWORDS**
biodiversity, characterization factors, energy system, industrial ecology, life cycle assessment, potentially disappeared fraction of species

## 1 | INTRODUCTION

Norway aims to cut its emissions in half by 2030 to meet the goals of international frameworks that promote climate change mitigation (OED, 2021)—the Glasgow Climate Pact, the Paris Agreement, and the UN Sustainable Development Goals (SDGs). Electrification and renewable energy stand at the heart of the country's climate plan (OED, 2021). Hydropower, wind, and thermal power accounted for 91.5%, 7.5%, and 1.1%, respectively, of Norway's electricity production in 2021 (SSB, 2022). The Norwegian government intends to continue the development of renewable energy production. The outlook toward the year 2040 suggests an increase in electricity production from renewable sources in Norway: further construction and upgrade of hydropower plants would produce an additional 10 terawatt-hours (TWh). Onshore and offshore wind power production could together increase by 11 TWh, and 7 TWh could be gained from solar power (NVE, 2020; OED, 2021). However, an increase in renewable energy resources will affect the grid network (ENTSO-E, 2021). That is especially true for new transmission power lines that link new electricity generation facilities with the distribution grid (IEA, 2021). The growing electrification in both the private and industrial sectors is set to increase electricity demand, thereby requiring a rapid expansion of power lines (IEA, 2021; OED, 2021). Since electrification is a significant component of Norway's climate plan, Norwegian grid companies plan to invest more than 140 billion NOK in the country's power grid until 2029 (OED, 2021).

On the other hand, Norway is committed to global initiatives to preserve nature and biodiversity, that is, the Aichi Targets and the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) (KMD, 2015). The further development of the electricity grid in Norway will increase, amongst others, the pressure on biodiversity. Habitat conversion, fragmentation, changes in the composition of populations, fire risk, and barrier effects are among the impacts that power lines pose on biodiversity (Biasotto & Kindel, 2018; Richardson et al., 2017). Moreover, power lines are often associated with collision and electrocution (Bernardino et al., 2018; Richardson et al., 2017), which kill hundreds of millions of birds annually on a global scale (Bernshausen et al., 2017; Loss et al., 2014; Rioux et al., 2013). Although researchers have been studying the effects of power lines on birds extensively since the early 1970s (APLIC, 2012; Bernardino et al., 2018), some knowledge gaps remain (Bernardino et al., 2018; Biasotto & Kindel, 2018; Richardson et al., 2017). For example, there is a need for models that can estimate the cumulative effects of the current and future grid networks (Bernardino et al., 2018; Biasotto & Kindel, 2018).

Life cycle assessment (LCA) is a method that assesses how a product (e.g., a power line) affects the environment during its entire life cycle (Bjørn et al., 2018; ISO, 2006). The life cycle of any product starts with raw materials extraction and continues with production and manufacturing, the use phase, and the end-of-life of a product or process. Today, LCA is used worldwide (Hellweg & i Canals, 2014). One of its key strengths is the simultaneous assessment and comparison of several environmental impacts (Verones et al., 2017). Through the quantification of multiple impacts, LCA facilitates an evaluation of the environmental performance of various products, enabling the identification of the most environmentally friendly option among them (Bjørn et al., 2018) and assisting decision-makers to promote sustainable solutions within the governmental and private sectors (Hellweg & i Canals, 2014; Owsianiak et al., 2018). Current LCA models analyzed the environmental effects of power lines primarily linked to climate change, eutrophication, and resource depletion impact pathways (Gargiulo et al., 2017). A methodology to quantify the impacts of electricity distribution systems on biodiversity does not yet exist. Recent life cycle impact assessment (LCIA) models quantified the effects of electricity production from hydropower (Dorber et al., 2019 , 2020) and wind power (May et al., 2020, 2021) on biodiversity in Norway and on a global scale. However, these models did not include the electricity grid infrastructure, which is essential for a holistic life cycle perspective.

We developed the first LCIA models that quantify the main impact pathways in the operational phase of power lines on bird diversity: collision and electrocution. To validate the models, we apply them to Norway, which intends to become a low-emission nation in the next 30 years (OED, 2021). Our methodology can show the potential impacts of expanding the Norwegian power grid on bird richness.

## 2 | METHODS

We developed models to assess the two impact pathways of power lines on the diversity of birds: collision and electrocution. Our models adapt the concept of species–area relationships (SAR), which is widely recognized as one of the fundamental and most studied patterns in ecology (Ladle & Whittaker, 2011; Lawton, 1999; Lomolino, 2000; Rosenzweig, 1995). SAR is a well-used tool to quantify impacts on biodiversity in LCA (Chaudhary et al., 2015; Kuipers et al., 2021; May et al., 2021; Woods et al., 2018). It describes the relationship between an area and the number of species it sustains. SAR can thus be used to predict how a decline in habitat size will reduce species richness. We quantified species loss in units of the potentially disappeared fraction of species (PDF), the recommended metric to assess ecosystem damage in LCIA (Verones et al., 2017; Woods et al., 2018). The PDF estimates the relative potential loss of species richness by a reduction in available habitat. The remaining area ($A_{new}$) from the original habitat size ($A_{org}$) affects the number of species remaining ($S_{new}$) in the habitat and lost ($S_{lost}$) from it. The $z$ value is a constant that indicates the slope of the SAR (Equation 1).

$$\frac{S_{new}}{S_{org}} = \left[\frac{A_{new}}{A_{org}}\right]^{z} \leftrightarrow S_{lost} = S_{org} - S_{org} \cdot \left[\frac{A_{new}}{A_{org}}\right]^{z} \rightarrow \text{PDF} = \frac{S_{lost}}{S_{org}} = \frac{S_{org} \cdot \left(1 - \left[\frac{A_{org} - A_{lost}}{A_{org}}\right]^{z}\right)}{S_{org}} \quad (1)$$

## 2.1 | Life cycle assessment

### 2.1.1 | Collision impact pathway

To quantify the impact of the collision, we quantify the PDF as a decrease in species richness due to bird collision with power lines ($S_{\text{at risk}}$). The number of species that are at risk of collision are species that use the "rights-of-way" (ROW), the area without vegetation, to assure a safety corridor between power lines and nearby trees or infrastructure (Equation 2).

$$\frac{S_{\text{at risk}}}{S_{\text{org}}} = \frac{S_{\text{org}} \cdot \left(1 - \left[\frac{A_{\text{org}} - \text{ROW}}{A_{\text{org}}}\right]^{z}\right)}{S_{\text{org}}} \tag{2}$$

We calculated the PDF for collision at the pixel level (1 $km^2$). Impact quantification was confined to pixels intersected by power lines, assuming that birds are affected only when they are present in areas with transmission or distribution lines. We predicted the decline in species richness based on the proportional remaining habitat area: the original habitat area ($A_{\text{org}} = 1$ $km^2$) is reduced by a collision risk probability (CRP) and the area of the rights-of-way ($\text{ROW}_{i,pl}$) of the power line type *pl*, distinguishing between transmission or distribution. We used species distribution maps of Norwegian birds to assess the spatial probability of their presence across Norway. 13 bird groups were included in the models. They consist of 271 species, aggregated into different groups based on taxonomy and ecological functionality (see Section 2.2.1). To calculate the total number of species ($S_{i,k}$), all species within bird group *k* were summed per pixel *i* across Norway. We used a Eurasia continental-scale *z* value of 0.21 (Storch et al., 2012) to create PDF rasters per bird group *k* (Equation 3).

$$\text{PDF(C)}_{i,k,\text{l}} = \frac{S_{i,k} \cdot \left(1 - \left(\frac{A_{\text{org}} - \text{CRP}_k \cdot \text{ROW}_{i,pl}}{A_{\text{org}}}\right)^{z}\right)}{\sum S_{i,k}} \tag{3}$$

Collision risk is highly dependent on species-specific traits (Bevanger, 1998). As flight maneuverability decreases with higher wing loading and lower wing aspect (Bernardino et al., 2018; Bevanger, 1998; Janss, 2000; Rubolini et al., 2005), we used the ratio of these two factors to evaluate the susceptibility of species to collisions. We considered the ratio to be proportional to the potential collision rates per bird group *k*. Similarly to May et al. (2020, 2021), who transformed wind power collision rates into a probability, we converted the wing loading and aspect ratio into a collision risk probability (Equation 4). Here, a higher wing loading and aspect ratio reduces the probability of no collisions and, consequently, also renders a higher collision risk probability.

$$\text{CRP}_k = 1 - P\,(\text{no collisions}) = 1 - e^{\frac{-\text{Wing loading}_k}{\text{Wing aspect}_k}} \tag{4}$$

### 2.1.2 | Electrocution impact pathway

PDF values for electrocution were computed per pixel (1 $km^2$) by the reduction in the original habitat area due to using a radius around each pylon based on half the total rights-of-way width ($\text{ROW}_{i,b,pl}$). For transmission lines, an average width of the rights-of-way was calculated per pixel *i*, while for the distribution lines, a width of 20 m was applied (NVE, 2016). This circular surface area was multiplied by the number of pylons ($P_i$) belonging to power line type *pl* per pixel *i* to account for pylon density. The combined factors of pylon area, electrocution risk probability (ERP), and pylon density contribute to the reduction of the original habitat area, resulting in a decrease in species richness (Equation 5):

$$\text{PDF}(E)_{i,k,pl} = \frac{S_{i,k} \cdot \left(1 - \left(\frac{A_{\text{org}} - \left(\left(\left(\pi \cdot (0.5 \cdot \text{ROW}_{i,b,pl})^2\right) \cdot P_{i,pl}\right) \cdot \text{ERP}_k\right)}{A_{\text{org}}}\right)^{z}\right)}{\sum S_{i,k}} \tag{5}$$

We calculated the electrocution probability risk by converting the ratio between wingspan per bird group *k* and distance phase-to-phase (Dpp) per pixel *i* to a probability. Larger birds have a higher chance of reaching the conductors when spreading their wings. Therefore, it increases their exposure to electrocution (APLIC, 2006). The wingspan measurement can therefore indicate an electrocution risk probability. In addition, pylons of distribution lines have a higher electrocution impact on birds, as the spaces among the conductors and between conductors and the grounded line are smaller (Eccleston & Harness, 2018; Lehman et al., 2007). The distance phase-to-phase indicates the distances between the phase conductors. So, a smaller space would generate a higher electrocution probability than a larger one. Furthermore, electrocution risk highly depends on the species' behavior. Birds that use pylons for perching or nesting are prone to electrocution (Eccleston & Harness, 2018; Lehman et al., 2007). Since a high pylon offers a good viewpoint for hunting and can attract predators (Eccleston & Harness, 2018), we assumed that birds that forage on the ground or above the canopy and mostly consume meat would have a higher probability of perching on pylons or power lines. Diet and foraging strata data were assigned to bird species to calculate pylon use behavior (PU). The pylon use behavior was averaged per bird group *k* and incorporated as a behavioral factor to assess the risk of electrocution. Birds tend to use pylons more frequently in open habitats that lack natural perching sites (Eccleston & Harness, 2018). Therefore, areas with lower tree cover are more likely to experience electrocutions. To account for this aspect, we subtracted the tree cover (TC) by 1, including it as an additional component in the electrocution risk probability. All these factors contribute to an increased electrocution probability (Equation 6):

$$\mathrm{ERP}_k = 1 - P\ (\text{no electrocutions}) = 1 - e^{\frac{-\mathrm{Wingspan}_k}{\mathrm{Dpp}_i} \cdot \mathrm{PU}_k \cdot (1-\mathrm{TC})} \tag{6}$$

### 2.1.3 | Aggregation to local characterization factors

We aggregated the PDFs for each impact pathway (X) and power line type by multiplying the PDF raster of each bird group *k* with the corresponding number of species within that group. Next, we summed the PDFs across all bird groups and divided the result by the overall number of species. The PDFs were extracted and summed for the five Norwegian pricing areas (PA). Final local characterization factors were derived by dividing the PDF by the total electricity (E) generated or consumed per kilowatt-hour (kWh) for 2021 within each pricing area (ENTSO-E, 2022; SSB, 2022) (Equation 7):

$$\mathrm{CF}(X)_{\mathrm{PA},pl} = \frac{\sum \mathrm{PDF}(X)_{i,k,\mathrm{PA},pl}}{E_{\mathrm{PA},pl}} \tag{7}$$

The collision and electrocution characterization factors for transmission lines, which facilitate the transfer of electricity from the power plants to the distribution grid, were derived by dividing the cumulative PDF by the amount of electricity generated. Conversely, the aggregated PDF of the collision and electrocution pathways for distribution lines, which supply electricity to end-users, were divided by the amount of electricity consumed.

Sensitivity analyses were conducted to observe the influences of three factors on the collision and electrocution models: the collision risk probability, pylon use behavior, and wingspan. For methodological description and results, see Supporting Information S2. The data analysis was computed with R 4.1.3 (R Core Team, 2020) in Rstudio 2021.9.0.351. The scripts and the related files are provided in the Supplementary Information section.

## 2.2 | Risk factors data

### 2.2.1 | Bird data

We included 271 bird species that live for at least part of the year in Norway. We aggregated them into 13 groups based on their taxonomy and ecological functionality following May et al. (2021): corvids, gallinaceous birds, gulls, owls, passerines birds (subdivided into herbivorous, insectivorous, polyphagous songbirds, and other bird species), raptors, seabirds, waders, waterbirds, and waterfowls. Morphological features play an important role in species' susceptibility to collision or electrocution (Bernardino et al., 2018; Bevanger, 1998; Eccleston & Harness, 2018; Janss, 2000; Loss et al., 2014). We collated measurement data of Norwegian birds on body weight (kg), wingspan (m), and wing area ($m^2$) (Bruderer et al., 2010; Bruderer & Boldt, 2001; Cornell Lab of Ornithology, 2021; Lislevand et al., 2007; Nord University, 2021; Oiseaux, 2021; Pennycuick, 2008; Vincze et al., 2019). Wing area measurements were not available for all birds. Therefore, we predicted wing area for the remaining 51 species with a log-transformed linear mixed-effects regression model regressing wing area against wingspan and weight with taxonomic family as a random effect (intercept: $0.029 \pm 0.17$ SD, $R^2 = 0.99$). Wing loading was calculated by dividing body weight by wing area and wing aspect by dividing the squared wingspan by wing area (Rayner, 1988).

To calculate the probability of birds using pylons (pylon use behavior), we derived species diet and foraging strata data from the EltonTraits (Wilman et al., 2014). The EltonTraits are fundamental characteristics that outline the role of species within the ecosystem, such as diet, foraging strata and time, and body size (see Supporting Information S1, Table S1). Species were assigned summed prevalence values for foraging on the ground or above the canopy. We did not include other foraging strata categories (i.e., understory of the forest, trees, and tree canopy), assuming species that forage in forests would not necessarily hunt in open habitats. As we focus on impacts on land, we chose to exclude the water foraging strata categories (i.e., below or on the water surface).

Species also received values representing the percentage of meat consumption if their diet primarily consisted of meat (i.e., mammals, birds, reptiles, unknown vertebrates, and scavengers) as compared to invertebrates and plants (i.e., fruits, nectars, seeds, and other plant parts). In cases where the species did not primarily consume meat, a value of zero was assigned. To obtain a final pylon use behavior value for each species, we multiplied the foraging strata data with the corresponding diet data. To calculate the mean and confidence intervals of the pylon use behavior per bird group $k$, we assumed a beta distribution because the values presented a probability distribution bounded between zero and one. To avoid calculation errors, a very small number ($1 \times 10^{-4}$) was added or subtracted from each value if it was originally zero or one.

#### 2.2.2 | Power line and pylon features

Geodata of power lines and pylons, including coordinates and electric tension in kilovolts (kV), were obtained from the Norwegian Resources and Energy Directorate (NVE) (NVE, 2021). Our dataset comprised central, regional, and distribution power lines. Transmission lines were classified as power lines carrying voltages exceeding 60 kV (APLIC, 2006), while distribution lines encompassed those with voltages lower than 60 kV. Sections lacking kV information, accounting for approximately 1% of the entire dataset, were excluded from the analysis. The width of the rights-of-way can vary due to multiple factors, such as voltage level, wire type, or arrangements with property owners (NVE, 2016). A 420 kV power line in Norway typically has a rights-of-way width of 40 m, 35 m for 300 kV, and 25–30 m for 132 kV (A. Granheim, Statnett, personal communication, June 18, 2021). We created 20, 17.5, and 13.75 m buffers around each power line based on its voltage level. Power line sections below 132 kV were given a 10 m buffer (NVE, 2016). We generated $1 \times 1$ km$^2$ grid cells across Norway and intersected each pixel with the buffered power lines. We calculated the area size of the rights-of-way within each pixel cell in km$^2$.

In Norway, pylons are commonly built using wood, while steel is a prevalent choice for the construction of transmission line pylons. Additionally, pylons may be constructed using materials like concrete and laminated wood (Rosvold, 2019). We assigned kV data from the power lines to their nearby pylons and removed features within less than 5 m distance from each other to avoid double records. Next, we created a map of pylon density with a spatial resolution of 1 km$^2$ for Norway. Each pixel contains the total number of pylons within it. We assigned distance phase-to-phase values to each pylon according to its electric voltage (see Supporting Information S1, Table S2) (DSB, 2006). Finally, we created a raster ($1 \times 1$ km$^2$) of Norway with a mean Dpp value of the pylons within each pixel.

#### 2.2.3 | Forest cover

We obtained tree cover density data for 2018 in Norway from the EU Copernicus Land Monitoring Service (EU Copernicus Land Monitoring Service, 2018). The $10 \times 10$ m maps were resampled to a resolution of 1 km$^2$, where the tree cover density was converted to a percentage and merged into a single raster.

### 2.3 | Mapping bird occurrences

The species distribution maps were conducted with MaxEnt (Phillips et al., 2017) with presence-only data from the Global Biodiversity Information Facility (GBIF) for Norwegian birds, as described in May et al. (2021). To address the presence of migratory birds that do not reside in Norway throughout the entire year, we classified each bird species based on its migratory status. The classification categories included fully resident, migratory or resident, and fully migratory (Billerman et al., 2022). We then applied a weighting factor to each map corresponding to the migratory status of each species (1, 0.75, and 0.5, respectively) to account for their annual presence in Norway. The updated maps, now reflecting the migratory statuses, were utilized to calculate the number of species ($S_{i,k}$) for the collision and electrocution PDFs.

### 2.4 | Norwegian pricing areas

In Norway, a significant spatial variation exists between electricity production and consumption. The country is divided into five different pricing areas, in which the supply and demand of electricity, and thus the price, varies: Eastern Norway (NO1), Southern Norway (NO2), Central Norway (NO3), Northern Norway (NO4), and Western Norway (NO5) (Statnett, 2022). Given that the majority of LCA studies that focus on energy systems utilize electricity units as a functional unit (i.e., kWh) (Laurent et al., 2018), we applied our models to the Norwegian pricing areas. This approach enables us to spatially quantify the biodiversity impacts by considering the electricity consumption and production within each pricing area.

### 2.5 | Norwegian electricity statistics

Norwegian electricity production data from 2021 were downloaded (ENTSO-E, 2022). Electricity production data provided hourly megawatt (MW) data from multiple energy sources (i.e., wind power, hydropower, and burning waste) in Norway for each pricing area. Data were converted to

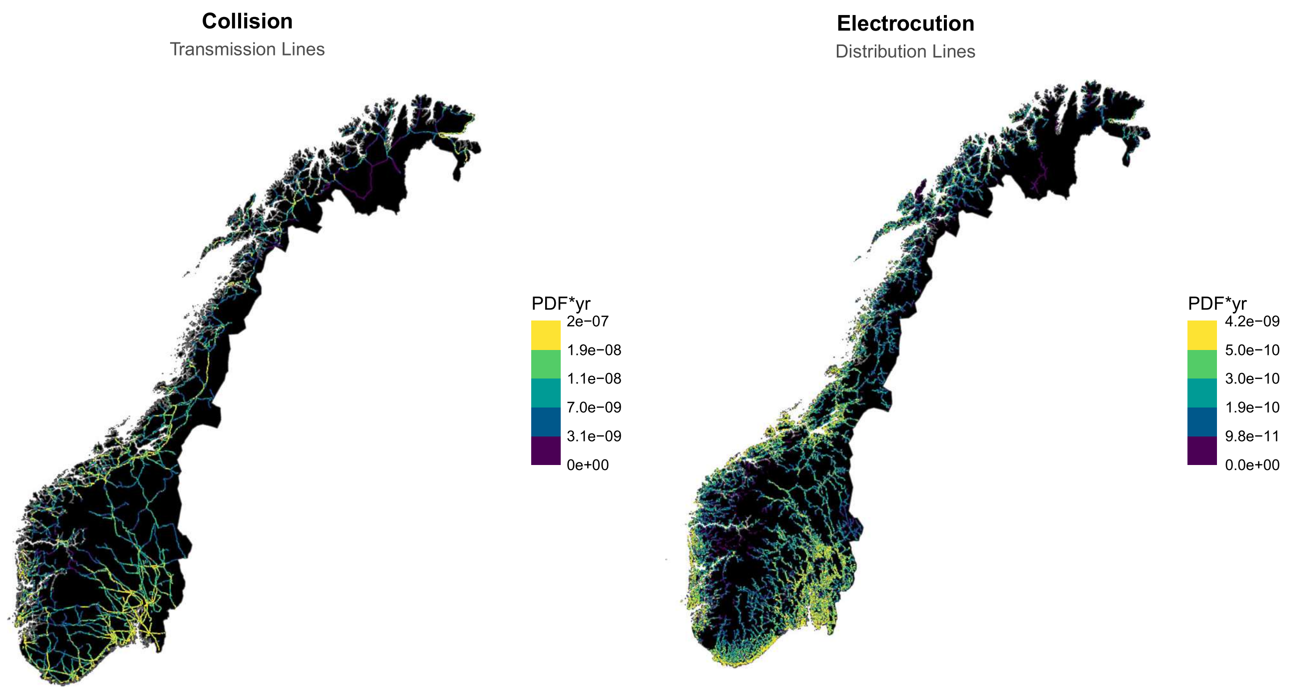


**FIGURE 1** Potentially disappeared fraction of species results for collision with transmission lines (left) and electrocution by distribution lines (right) impact pathways in Norway. Underlying data for this figure are available in the Zenodo repository.

annual kWh per pricing area. Data on electricity consumption per municipality in 2021 were obtained (SSB, 2022). We summed municipal electricity consumption per pricing area based on the largest share of overlap within each pricing area.

## 3 | RESULTS

We generated PDF maps per impact pathway and power line type for 13 bird groups consisting of 271 species. For the collision impact pathway, we assessed the potential impact of 34,311 km of transmission lines and 58,885 km of distribution lines. In the electrocution model, we incorporated 98,034 high-voltage pylons and 560,669 low-voltage pylons across Norway.

### 3.1 | Potentially disappeared fraction of species

We calculated an annual average impact for collision and electrocution for the Norwegian grid network: the collision impact of transmission lines was $3.17 \times 10^{-4}$ PDF*yr, while the distribution lines resulted in a yearly impact of $5.86 \times 10^{-4}$ PDF*yr. For electrocution, the high-voltage pylons had a PDF*yr of $1.38 \times 10^{-6}$, and the low-voltage pylons had a PDF*yr of $1.65 \times 10^{-5}$. The collision impact varied from $1.6 \times 10^{-15}$ to $2.03 \times 10^{-7}$ PDF*yr for transmission lines and from $8.83 \times 10^{-16}$ to $1.41 \times 10^{-7}$ PDF*yr for distribution lines. The electrocution impacts ranged from $1.67 \times 10^{-12}$ to $2 \times 10^{-9}$ PDF*yr for transmission lines and from $4.1 \times 10^{-12}$ to $4.21 \times 10^{-9}$ PDF*yr for distribution lines. Regions with higher PDF values due to bird collisions were primarily observed along the transmission lines in Southern and Central Norway. Distribution lines posed a greater risk in terms of PDF for collision and electrocution in Southern Norway and along the west coast. Transmission lines had a high PDF for the electrocution impact pathway in sections in Southern and Northern Norway (Figure 1 and Supporting Information S2, Figures S1-2).

### 3.2 | Regional characterization factors

Characterization factors were calculated per pricing area for the collision and electrocution impact pathways and power line type. The characterization factors for collision varied between $8.48 \times 10^{-16}$ and $5.6 \times 10^{-15}$ PDF*yr/kWh, while for electrocution, they ranged between $3.27 \times 10^{-18}$ and $1.66 \times 10^{-16}$ PDF*yr/kWh. We estimated a lower efficiency of electricity distribution regarding its collision and electrocution impacts on species richness (i.e., PDF/kWh) in pricing areas one, three, and four (Figure 2, Supporting Information S1, Table S8, and Supporting Information S2, Figures S3-4).

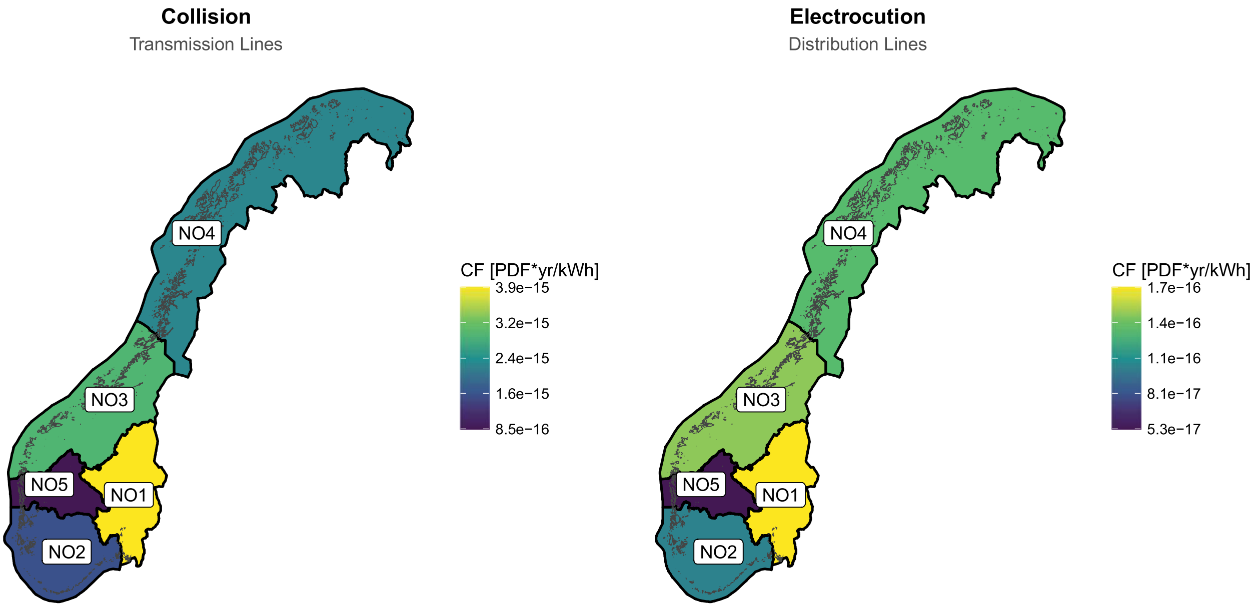


**FIGURE 2** Characterization factors quantifying the impact of electricity consumption on bird richness in potentially disappeared fraction of species*yr/kWh due to collision with transmission lines (left) and electrocution by distribution lines (right). Underlying data for this figure are available in Table S8 of Supporting Information S1.

### 3.3 | Estimated impacts on bird groups

Power lines affect species differently among bird groups and impact pathways, as seen in Figure 3. Collision posed a greater threat to gallinaceous, waterfowls, and waterbirds. Raptors, owls, and corvids were more susceptible to electrocution (see Supporting Information S1, Table S7). Uncertainties for wing area, collision risk probability, wingspan, and bird behavioral measurements can be found in the Supporting Information (Supporting Information S1, Table S3-6).

## 4 | DISCUSSION

In this study, we presented the first approach to assess the impacts of an electricity grid network on bird richness within the LCIA framework. The developed regional characterization factors for collision and electrocution show which bird groups are vulnerable and which areas encompass a higher risk.

Identifying bird mortality hotspots due to collision and electrocution of power lines is essential, as it can highlight which power lines should be upgraded with mitigation measurements. Moreover, it can assist in prioritizing areas where the construction of power lines should be avoided to protect biodiversity and thus contribute to sustainable decision-making. Common evaluation and quantification tools assessing the mortality of birds colliding with power lines rely mostly on field surveys recording bird carcasses along power lines (Bernardino et al., 2018). These field surveys offer a limited spatial extent, as they are confined to their study sites. Recently developed models have demonstrated the efficacy of spatial models in prioritizing susceptible species or infrastructure and identifying areas with a high risk for collision (D'Amico et al., 2019; Paquet et al., 2022) and electrocution (Biasotto et al., 2022; Eccleston et al., 2023; Hernández-Lambraño et al., 2018; Pérez-García et al., 2017). Our approach can be applied on a large scale, for example, national scale, as we showcase for Norway, and be integrated into the LCA framework. This is helpful for environmental decision-making because LCA allows assessing multiple impacts (e.g., global warming, pollution, and habitat loss) across different life cycle stages (e.g., construction, operation, and decommissioning of power infrastructure) in a comparative manner and therefore highlights where trade-offs and synergies may occur in a larger, system-wide assessment.

The results indicate that collision has a greater impact on bird diversity (i.e., higher PDF). Research has shown that bird collision results in higher annual mortality rates compared to electrocution (Loss et al., 2014). While the focus of studies on bird collisions has primarily been on transmission lines rather than distribution lines (Bernardino et al., 2018), it has been demonstrated that birds also collide with low-voltage lines (Gális et al., 2020; Shaw et al., 2018; Škorpíková et al., 2019). Given the extensive distribution grid in comparison to the transmission network, it may come as no surprise that distribution lines induced a higher collision impact. Multiple factors can increase collision risk for birds. The ability of a bird to perceive the

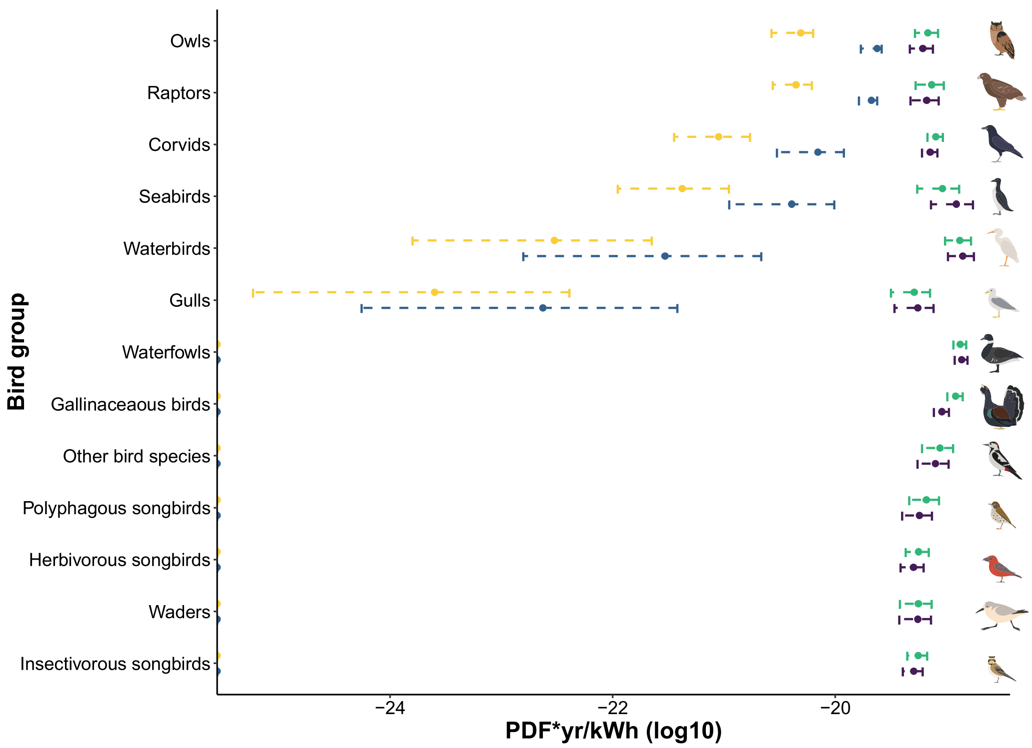


**FIGURE 3** Potentially disappeared fraction of species of species richness per bird group per electricity production and consumption (kWh) for collision impact pathway with transmission lines (green line) and distribution lines (purple line) and for electrocution by transmission lines (yellow line) and distribution lines (blue line). Electrocution impacts for the lower seven bird groups were zero. Underlying data for this figure are available in Table S7 of Supporting Information S1.

environment with its eyes may play a role. For instance, birds with binocular sight have a better chance of noticing and avoiding obstacles (Martin, 2011; Martin & Shaw, 2010). Behavioral factors may also affect species' vulnerability to collision, that is, gregarious species that fly together as a flock, migratory birds unfamiliar with the area, nocturnal birds with limited visibility, and birds that display aerial courtship or defend their territories. Furthermore, species-specific factors, that is, sex, age, and flight height, clearly affect bird collisions with power lines (Bernardino et al., 2018). We, however, chose to quantify collision risk only using wing aspect and wing loading for several reasons. First, previous studies have shown that wing morphology successfully predicts the probability of a species colliding with power lines (Bevanger, 1998; Janss, 2000; Rubolini et al., 2005). Second, although other aspects may affect collision risk, such data are difficult to collect or quantify. In addition, the contribution of these aspects to a probability risk remains unknown. Third, body measurement data were available for many Norwegian species. Although we did not obtain wing area data for all species, our linear-mixed effect regression model successfully predicted measurements for the remaining species. Finally, our sensitivity analysis showed a limited variation in the PDF values based on changes in the collision risk probability (see Supporting Information 1, Tables S10-14 and Supporting Information S2, Figures S5-9).

Mitigation measures can decrease the risk of collision. For example, attaching markers to the wires can enhance the visibility of power lines and reduce bird collisions (APLIC, 2012; Barrientos et al., 2012). This approach has proven effective in Norway, where spiral markers altered bird flight behavior, thereby contributing to a decrease in the risk of collisions (Pavón-Jordán et al., 2020). However, the national electric grid dataset lacks information regarding the presence of markers. Once available, this information can be integrated into our models, allowing for a targeted reduction in collision impact within sections where markers were implemented.

Similarly to collision, the risk of electrocution is dependent on several components. Dwyer et al. (2016) suggested a conceptual model that links electrocution hazard, avian exposure, and avian electrocution risk. Our model addresses all three. The configuration of the pylons plays an important role in the electrocution risk, as pylons with certain features can cause many casualties (Dwyer et al., 2014; Hernández-Lambraño et al., 2018; Kolnegari et al., 2021). For instance, a design of cross-arms or pylons with pole-mounted equipment (i.e., transformers) (Eccleston & Harness, 2018; Hernández-Lambraño et al., 2018). This indicates that certain pylons can present an exceptionally high risk of electrocution in comparison to others (Bevanger et al., 2010; Eccleston et al., 2023; Hernández-Lambraño et al., 2018). However, a detailed dataset mapping the design of each pylon in Norway was not available. We attempted to address the hazard level of pylons by using the distance between phases as a proxy. Yet by excluding the technical design of individual pylons, our approach may lead to an overestimation of the electrocution impact. Further development of our model must integrate the required technical information of pylons to demonstrate the direct impact of singular dangerous pylons. Our models would benefit if local providers shared their spatial data, particularly information about pylon types and their designs. Alternatively, this information could be achieved by developing a predictive model to assess the electrocution risk, similar to the models presented by Eccleston et al. (2023) or Hernández-Lambraño et al. (2018).

We included two elements of exposure: pylon density and tree cover. Pylon density is a known factor in electrocution risk (Dwyer et al., 2020; Pérez-García et al., 2011), while the lack of tree cover is assumed to increase pylon use due to the lack of natural perching sites (Tintó et al., 2010). Furthermore, the species distribution maps provided a base layer concerning the presence of species, thereby highlighting areas of risk for birds.

Since the size and behavior of birds play an important role in electrocution risk (Bevanger, 1998; Eccleston & Harness, 2018; Loss et al., 2014), we emphasized these two factors for predicting an electrocution risk probability. Rather than assuming that larger birds are more susceptible to electrocution, we linked the wingspan measurements to the distance between phases. We used the species-specific EltonTraits to identify birds that may perch on power lines or pylons. Therefore, our results for electrocution are limited only to certain bird groups, excluding species belonging to other groups that may become electrocuted. For instance, pigeons (Pérez-García et al., 2011; Tintó et al., 2010), which are assigned to the "other bird species" group. Additional behavioral traits (e.g., nesting) may be beneficial to include for other bird groups. Yet such behavioral data specifically related to power line usage across multiple species were, to our knowledge, unavailable.

By modeling impacts within the LCIA framework, we compared how power lines affect bird richness across Norway. However, LCA accepts a high uncertainty in its models, such as the true location of the power lines. The large national dataset of pylons that we used dated from 2021, yet it originates from data collection performed in 2009, which may not be fully updated (C. Kvamme, NVE, personal communication, June 7, 2021). In addition, although several sections were excluded from the transmission and distribution lines because they did not have voltage data, the missing data accounted for less than 1% of the grid network data. We believe this database offers the best available representation of the Norwegian grid. Furthermore, we used species distribution maps that predicted suitable habitats, not the true localities of bird species. Also, we did not refer to birds' migratory routes but classified the species into migratory categories to assess how often they are present in Norway within one year. Finally, the absence of comprehensive empirical data on bird collisions and electrocutions in Norway has hindered our ability to conduct a validation analysis. Alternatively, our models could be compared with other spatial models that assess the risk of power lines for bird richness in Norway. For example, the models recently developed by Sicacha-Parada et al. (2023), which combine professional field surveys and citizen science data.

The collision and electrocution impacts we modeled are limited locally to Norway. While species may disappear locally in Norway, they might persist globally. A global model is needed to obtain comparable results among regions and countries, highlighting where power lines cause higher global impacts on bird richness. A local model, however, can provide a more accurate result as it relies on smaller scales. By feeding our models with appropriate input data, they can be applied to other regions to highlight the potential impacts of power lines. This is especially true for North European countries with similar bird species. Other data, for example, the locations of power lines or forest cover, are available globally (Arderne et al., 2020; Buchhorn et al., 2020).

Our models showed how collision and electrocution affect bird groups differently. Waterfowls, waterbirds, and gallinaceous birds received higher PDF values compared to the other bird groups. The species within these groups belong largely to the orders of Anseriformes, Galliformes, Gruiformes, Podicipediformes, and Pelecaniformes, which are known to suffer casualties by colliding with power lines (Bernardino et al., 2018; Rubolini et al., 2005; Škorpíková et al., 2019). Birds of prey are often the victims of electrocution, especially species of the orders Accipitriformes, Falconiformes, and Strigiformes (Bevanger, 1998; Janss, 2000; Lehman et al., 2007). Crows, ravens, and magpies are also regarded as susceptible to electrocution. Our electrocution model also suggests gulls, seabirds, and waterbirds as potential casualties due to electrocution. Storks, gulls, and cormorants are sometimes mentioned as electrocution victims (Pérez-García et al., 2011; Tintó et al., 2010), indicating that birds of prey are not the sole victims of electrocution (Guil & Pérez-García, 2022). Moreover, a field survey on the Island of Smøla in Norway showed a high proportion of gulls as electrocution casualties (Bevanger et al., 2010).

There are variabilities between the impacts and their magnitude across Norway. In Southern Norway, particularly within the densely populated Oslo region and along the coast, transmission lines have higher PDF values for collision compared to Northern Norway. The Southwestern coastal area of Norway, characterized by narrow fjords and mountains, requires an extensive infrastructure of power lines to reach all consumers. A higher risk of electrocution by transmission lines is observed in Southern and Northern Norway, where medium-voltage pylons are located. Distribution lines pose a threat of collision and electrocution in South Norway. Additionally, along the country's western coast, we can see high PDF values (Figure 1).

The characterization factors highlight the risk of collision and electrocution in pricing areas one, three, and four (see Figure 2 and Supporting Information S2, Figures S3-4). Pricing area one is impacted by collision and electrocution because it is home to many bird species, putting a larger number of species at risk. It relies heavily on electricity imports and has the highest number of pylons, which contributes to the high electrocution impact. Pricing area three is ranked as the second most affected region due to its coastal bird habitats and extensive network of transmission lines. Pricing area four, with fewer species, is still greatly impacted because of its elongated shape and sparse population. In contrast, pricing area five faces fewer risks due to its short coastline and fewer power lines and pylons.

Although it is not in the interest of Norwegian companies to extend the electricity grid more than necessary, the upgrading and new construction of transmission and distribution lines are unavoidable. As Norway's potential to expand its energy capacity from renewable energy remains strong, this will lead to further development of renewable energy technologies, for example, hydropower, wind power, and solar power. Furthermore, the distribution grid capacity must increase to achieve the expected electrification within the industry and transport sector (OED, 2021). Our methodology is the first to quantify the impacts of power lines on bird diversity, highlighting populated areas around Oslo and the Southwestern Norwegian coast as sites with high collision risk. It also indicated a higher risk of birds getting electrocuted in Southern Norway along the western coast.

To arrive at a more holistic impact assessment of power lines, further impact pathways should be added. This includes, for instance, habitat conversion and fragmentation (Kuipers et al., 2021). In addition, most of the models could profit from including more taxonomic groups that are affected by power lines, for example, mammals. Integrating the impacts of power lines on biodiversity in LCA models of energy systems is important, as harmonized models can present a holistic assessment: estimating the effects of the production and consumption of electricity.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in Zenodo at https://doi.org/10.5281/zenodo.10624157.

## ORCID

*Dafna Gilad* https://orcid.org/0000-0001-7129-1421
*Roel May* https://orcid.org/0000-0002-6580-4064
*Bård G. Stokke* https://orcid.org/0000-0001-5589-6738
*Francesca Verones* https://orcid.org/0000-0002-2908-328X

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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