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## Biodiversity on the line: life cycle impact assessment of power lines on birds and mammals in Norway

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E-mail: [dafna.gilad@nina.no](mailto:dafna.gilad@nina.no)**Keywords:** life cycle assessment (LCA), collision, electrocution, fragmentation, habitat conversion, birds, mammalsSupplementary material for this article is available [online](#)

## Abstract

The global shift towards renewable energy plays an important role in fighting climate change. To facilitate the global growth of renewable energy production, the expansion of the electric grid becomes inevitable. Yet further construction of power lines poses a risk to biodiversity. Power lines traverse natural habitats and can lead to habitat conversion, fragmentation, and loss. Moreover, due to collisions and electrocutions, power lines kill hundreds of millions of birds each year. These impacts, however, have so far not been incorporated into decision-making. Life cycle assessment (LCA) is a widely used framework to compare environmental impacts and support decision-makers in planning and promoting sustainable strategies. We adapted existing life cycle impact assessment (LCIA) models to quantify the three main impacts of power lines on biodiversity: collision, electrocution, and habitat conversion and fragmentation. Our models incorporated species-area and species-habitat relationships to assess the effects of power lines on the diversity of birds and non-flying mammals in Norway, as the country is currently committed to reducing its emissions by expanding its renewable energy capacity. Overall, habitat conversion and fragmentation had the highest impact across the three impact categories, particularly affecting mammal richness. Furthermore, distribution lines often affected species richness more than transmission lines. The effect of the three impact pathways varied among different species groups, highlighting the vulnerability of certain species to habitat change, collision, and electrocution. Integrating LCIA models that quantify the impacts of power lines on biodiversity into LCA can support decision-makers with tools to promote the development of the electric grid without overlooking its effect on species richness. In addition, our models set the stage for a comprehensive assessment of the effects of electricity generation and transmission on biodiversity.

## 1. Introduction

Increasing renewable energy production is key to mitigating climate change [1]. Therefore, a steep increase in the global capacity of renewables is anticipated in the coming years [2–4]. To facilitate the energy transition, electricity networks must be upgraded or expanded to support the growing capacity of renewable energy [2, 3]. In addition, increased demand for electricity due to electrification, especially in the transport and heat sectors, will require modernization and further expansion of power lines [2, 3]. Consequently, the current 100 million kilometers of power lines globally are predicted to double in length in the coming decades [3].

Increased access to energy and clean, renewable energy production are two important objectives for achieving the seventh Sustainable Development Goal (SDG) and contributing to SDG 13 on climate action [5]. However, the growth in renewable energy and the expansion of the electric grid will contribute to ongoing pressure on biodiversity and thus lead to trade-offs with SDGs 14 and 15 (life below water and life on land, respectively). The main impacts caused by power lines are the death and injury of hundreds of

millions of birds due to collision and electrocution [6–8] and the change in habitat caused by the removal of vegetation [7]. The rights-of-way, the area cleared from vegetation, can be up to 100 m wide and cross natural habitats across long stretches of land [9, 10]. Its construction can affect habitat size and fragment landscapes for species of different taxa, especially birds and mammals [7, 11, 12].

To better understand how these impacts affect biodiversity, we require a comprehensive impact assessment framework. Such a system will also allow us to identify strategies for mitigating these impacts and minimizing the trade-offs between the SDGs.

Life cycle assessment (LCA) is an appropriate framework for comprehensively analyzing the environmental impacts of energy systems. It is a methodology that quantifies impacts throughout the life cycle of a product or a service [13]. LCA is known for its ability to compare multiple impacts simultaneously while incorporating a spatial dimension, indicating where they occur [13, 14]. In addition, LCA can identify potential trade-offs along the various phases of a product's life cycle [13]. This can highlight how efforts aimed at mitigating one impact pathway (e.g. promoting renewable energy to reduce emissions) can potentially impact other pathways (e.g. negatively affecting ecosystems) [13].

Furthermore, numerous LCA studies have focused on energy systems [15, 16], particularly emphasizing the environmental benefits of renewable energy technologies over fossil fuels [13, 16, 17]. This framework has also been used to model future scenarios, indicating the potential environmental impacts of promoting renewable energy [13, 18, 19].

The integration of biodiversity impacts in LCA has evolved rapidly in the past decades [20], including impacts related to energy production. New characterization factors have recently been developed to assess the effects of land inundation on terrestrial biodiversity due to the expansion or creation of freshwater reservoirs [21], water consumption of reservoirs on aquatic biodiversity [22], and global and regional impacts of wind farms on bird richness [23, 24]. These models, however, quantify only the effects of energy generation, neglecting the associated impacts of electricity transmission. Furthermore, although existing LCA studies on the environmental effects of power lines address multiple impact categories, they do not consider impacts on biodiversity [25].

A recently proposed methodology [26] quantified the impact pathways of power lines' collision and electrocution on bird richness. However, since these impacts primarily affect avian species, the effects of power lines on other terrestrial taxonomic groups are still unclear. Mammals, for instance, are frequently studied in relation to power lines [7].

Other available life cycle impact assessment (LCIA) models quantify the effects of habitat conversion and fragmentation on multiple taxonomic groups, including birds, mammals, amphibians, and reptiles [27, 28]. Nevertheless, these large-scale models only assess a limited number of land-use types. They overlook the potential impacts of infrastructure on biodiversity, which converts and fragments habitats [7].

This paper aims to adapt the LCIA habitat conversion and fragmentation models [27, 29] for power lines and to complement the work of [26] in order to evaluate the impacts of electricity transmission on the richness of birds and non-flying mammal species (hereafter referred to as 'mammals') within the LCIA framework. We selected Norway as a case study to demonstrate our methodology. Norway has developed a climate plan aimed at reducing emissions and increasing renewable energy production capacity, with the ambition of becoming a low-emission country by 2050 [30, 31]. The expansion of the Norwegian power line network is inevitable; given the necessity to upgrade and expand the Norwegian grid to enhance electricity transmission capacity [32–34], a governmental action plan to facilitate a faster concession process for constructing new power lines has been recently developed [35]. In addition, there are existing biodiversity LCIA models [22, 24] and life cycle inventory data [22, 36] that quantify the impacts of renewable energy production in Norway.

## 2. Methods

The LCIA framework often quantifies impacts on terrestrial biodiversity using species-area relationship (SAR) models [21, 37, 38]. The SAR model is founded on the principle that a reduction in habitat area results in a decrease in the number of species that reside in that area [39]. LCIA measures the loss of species in units of the potentially disappeared fraction of species (PDF) [14, 38].

To quantify the impacts of collision and electrocution on bird richness, we used the methodology developed by [26]. As the current knowledge on the electrocution of arboreal mammals is anecdotal [40–43], we limit our analysis to birds only. To quantify the impacts of habitat conversion and fragmentation on bird and mammal richness in Norway, we adapted the global LCIA models by [27, 29] using the developed species-habitat relationship (SHR) model, which integrates the SAR model with the equivalent connected area (ECA) concept.

## 2.1. Species distribution maps

We used species distribution maps rather than relying on large-scale species range maps that assume species are distributed equally across large areas. Our distribution maps estimate the likelihood of a species occurring across Norway. Distribution maps for bird species were retrieved from [24].

To produce maps for mammals, we followed the approach described by [24]. We obtained presence-only observation records for all mammals listed by Artsdatabanken [44] from the Global Biodiversity Information Facility (GBIF) (see supporting information, table S3). These records included all available data points compiled in Norway between 2010 and 2019. We modeled mammalian species with at least 200 GBIF records to remove vagrant species and species with insufficient data for reliable models [45].

The dataset was split into 50% training and 50% testing data to validate the models. Cell duplicates were removed, and species distribution maps were created with MaxEnt [46] in R Version 4.2.2 [47] using the package 'dismo' [48]. The following nine environmental predictors (with 1 km<sup>2</sup> resolution) were included in the MaxEnt models: annual mean temperature (°C), temperature seasonality (standard deviation \* 100), annual precipitation (mm), precipitation seasonality (coefficient of variation), digital elevation model, latitude, land cover, and distance to sea (AR50, Norwegian Mapping Authority), and terrain ruggedness index (Norwegian Water Resources and Energy Directorate (NVE)). The four climate predictors were obtained from WorldClim 2.0 [49], referring to data collected between 1970 and 2000.

The maps were calculated per species and aggregated into groups with similar taxonomy and functionality. As described by [24], bird species were grouped into 13 groups: corvids, gallinaceous birds, gulls, owls, herbivorous songbirds, insectivorous songbirds, polyphagous songbirds, other passerines species, raptors, seabirds, waders, waterbirds, and waterfowls. Mammalian species were aggregated into four groups: carnivores, other species, rodents, and ungulates. Bats were excluded from the analysis for several reasons. First, bats tend to be less susceptible to the negative effects of habitat fragmentation when compared to non-flying mammals [50]. Second, some bat species may respond positively to fragmented landscapes [50]. However, the primary limitation preventing the inclusion of bats in our analysis was the unavailability of dispersal data for bat species, a challenge also mentioned by [27].

To account for the annual presence of migratory bird species in Norway, we applied a weighting approach based on the migratory status of bird species. Each species map was multiplied by a corresponding factor, depending on the migratory status of the bird: fully resident, resident or migratory, and fully migratory (1, 0.75, and 0.5, respectively).

## 2.2. LCA

### 2.2.1. PDF of species

The PDFs were computed using the methodology outlined in [26, 27] (see table 1). For the constant  $z$ , which represents the slope of the SAR, we assigned the values 0.21 for birds and 0.26 for mammals [51].

The collision PDF was calculated as a decrease in species richness using a collision risk probability (CRP) averaged per bird group  $k$ . The CRP was derived from species-specific measurements (wing loading and wing aspect), which predict the species' flight maneuverability [6, 52] (equation (1)). We quantified the collision impact on the transmission and distribution grid as birds collide with them [6, 40, 53]

$$CRP_k = 1 - e^{\frac{-Wing\ loading_k}{Wing\ aspect_k}} \quad (1)$$

The PDF of electrocution quantified the reduction in species richness of susceptible species using an electrocution risk probability (ERP). The ERP took into account species-specific morphological (wingspan) and behavioral features (diet and strata; PU), the distance between phases ( $D_{pp}$ ) of the pylons per pixel  $i$ , and the percentage of tree cover (TC) subtracted by one to highlight open habitats. Open habitats induce more cases of electrocution because of the lack of natural features [54, 55] (equation (2))

$$ERP_k = 1 - e^{\frac{-Wingspan_k}{D_{pp_i}} \cdot PU_k \cdot (1 - TC)} \quad (2)$$

Since the gaps between the phases of high-voltage power lines are typically large [54, 56], the likelihood of a bird getting electrocuted by a transmission line is low. Statnett (Norway's national grid system operator) collects records of collision and electrocution incidents that cause outages (unpublished data spanning from the early 1900s to 2022). Only about one percent of the documented electrocution incidents occurred on transmission lines. Therefore, the electrocution impact was calculated only for distribution lines, i.e. less than 60 kilowatts [56].

The habitat conversion and fragmentation PDF was computed as the loss of species richness by habitat suitability and the decrease of the ECA within the Norwegian landscape regions (table 1).

**Table 1.** The adapted equations to calculate the potential disappeared fraction of species (PDF) from [26] and from [27] and their defined parameters.

| Impact                                     | Equation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|--------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Collision (C)                              | $\text{PDF(C)}_{i,k,pl} = \frac{S_{i,k} \cdot \left( 1 - \left( \frac{A_{org} - \text{CRP}_k \cdot \text{ROW}_{i,pl}}{A_{org}} \right)^z \right)}{\sum S_{i,k}}$ <p> <math>S_{i,k}</math> = number of species present in pixel <math>i</math> within species group <math>k</math><br/> <math>A_{org}</math> = pixel size (1 km<sup>2</sup>)<br/> <math>\text{CRP}_k</math> = probability of annual collision within species group <math>k</math><br/> <math>\text{ROW}_{i,pl}</math> = area size of rights-of-way in pixel <math>i</math> (km<sup>2</sup>) of power line type <math>pl</math><br/> <math>z</math> = constant indicating the slope of the SAR </p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Electrocution (E)                          | $\text{PDF(E)}_{i,k,pl} = \frac{S_{i,k} \cdot \left( 1 - \left( \frac{A_{org} - \left( \left( \pi \cdot (0.5 \cdot \text{ROW}_{i,b,pl})^2 \right) \cdot P_{i,pl} \right) \cdot \text{ERP}_k}{A_{org}} \right)^z \right)}{\sum S_{i,k}}$ <p> <math>\text{ROW}_{i,b,pl}</math> = average width of the rights-of-way in pixel <math>i</math> of power line type <math>pl</math><br/> <math>P_{i,pl}</math> = number of pylons in pixel <math>i</math> of power line type <math>pl</math><br/> <math>\text{ERP}_k</math> = probability of annual electrocution within species group <math>k</math> </p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| Habitat conversion and fragmentation (HCF) | $\text{PDF(HCF)}_{k,g,j,pl} = \frac{S_{j,k} \cdot \left( 1 - \left( \frac{h_{k,g,j,f} \cdot \text{ECA}_{k,g,f,j,b,pl} + h_{k,g,j,o} \cdot \text{ECA}_{k,g,o,j,b,pl}}{h_{k,g,j,f} \cdot \text{ECA}_{k,g,f,j,\text{ref},pl} + h_{k,g,j,o} \cdot \text{ECA}_{k,g,o,j,\text{ref},pl}} \right)^{z_g} \right)}{\sum S_{i,k}}$ <p> <math>S_{j,k}</math> = number of species present in landscape region <math>j</math> within species group <math>k</math><br/> <math>h</math> = habitat affinity of species group <math>k</math> of taxon <math>g</math> in habitat type forest (<math>f</math>) or open habitat (<math>o</math>) in landscape region <math>j</math><br/> <math>\text{ECA}_{k,g,j}</math> = effectively connected area for species group <math>k</math> of taxon <math>g</math> in habitat type forest (<math>f</math>) or open habitat (<math>o</math>) in landscape region <math>j</math><br/> <math>b</math> = habitat conversion and fragmentation impact with changed resistance (fragmentation effect) of power line type <math>pl</math><br/> <math>\text{ref}</math> = habitat conversion and fragmentation impact without change in resistance of power line type <math>pl</math> </p> |

Kuipers *et al* [27] calculated characterization factors for the four land types cropland, forestry, pasture, and urban. However, as trees must be removed from the rights-of-way to allow access and reduce the risk of outages [10], we only quantified the impacts on forests and open habitats. The habitat suitability was calculated separately for the two habitat types by computing the ratio between the mean number of species ( $S_{k,g,c,j}$ ) residing in habitat type  $c$  (i.e. forest or open habitat) within landscape region  $j$  and the maximum number of species ( $S_{k,g,j}$ ) found in the landscape region  $j$  (equation (3)). A high value would indicate that habitat type  $c$  is more suitable to support many species. In contrast, a lower value would suggest that the habitat may be inadequate, and species might avoid it. The habitat suitability was computed for each species group  $k$  within taxon  $g$  (i.e. 13 bird groups and four mammal groups)

$$h_{k,g,c,j} = \left( \frac{S_{k,g,c,j}}{S_{k,g,j}} \right)^{1/z_g} \quad (3)$$

The ECA represents the effectively connected area in kilometers and is generated for each species group  $k$  of taxon  $g$  in habitat  $c$  within landscape region  $j$ . [27] compared a reference ECA and a current ECA to calculate the PDF. The reference ECA was based on a potential natural vegetation map, representing global land cover conditions before anthropogenic land use. Land use data from 2015 were used to present the changes induced by humans to generate the current ECA. Since the analysis is conducted at a pixel level, and power lines often cover only a small portion of a pixel, there is a risk of overestimating the impacts. To address this, we focused solely on the current state to calculate ECA, i.e. after the construction of power lines. The PDF is then derived from the difference in ECA between the two resistance layers. A resistance layer is a raster indicating species movement probability through pixel  $i$ . Resistance increases with decreasing suitability of the area for species richness. Resistance is therefore calculated as one minus the ratio between the number of species in pixel  $i$  and the maximum number of species within landscape region  $j$  (equation (4)). The resulting values range between zero and one, with lower values indicating lower resistance and more suitable habitat conditions for species richness.

In comparison, higher values suggest a hostile habitat with high resistance. We generated a land cover raster for each power line type  $pl$ , which fragmented the landscape differently. Based on species distribution maps, resistance values were calculated for each species group  $k$  within taxon  $g$ .

$$r_{ref,i,k,g,pl,j} = 1 - \frac{S_{i,k,g,j,pl}}{S_{k,g,j,pl}} \quad (4)$$

An initial resistance layer was set as the reference state, indicating how species move between the pixels, i.e. the landscape, independent of the electric grid. To create the current state of the resistance layer, the values of the reference resistance raster were altered whenever a pixel ( $A_{org}$ ; 1 km<sup>2</sup>) intersected with a power line. The original resistance value was multiplied by the remaining area in the pixel ( $A_{new}$ ) and then increased by the lost area ( $A_{lost}$ ) due to power lines construction (equation (5)).  $A_{lost}$  is multiplied by the maximum resistance value of 1; highlighting the impacts of habitat conversion and fragmentation caused by power lines in that area

$$r_{i,k,g,c,j,pl} = \left( \left( 1 - \frac{S_{i,k,g,j,pl}}{S_{k,g,j,pl}} \right) \cdot A_{new,i} \right) + (1 \cdot A_{lost,i}) \quad (5)$$

The calculations for  $A_{new}$  and  $A_{lost}$  differed depending on habitat type  $c$  and power line type  $pl$ . For forests, the  $A_{lost}$  represents the cumulative area of the rights-of-way within pixel  $i$  in km<sup>2</sup>. For open habitats,  $A_{lost}$  accounts for the total area of the pylons within pixel  $i$ . We assumed that a pylon's diameter would depend on the width of the rights-of-way it stands in. Therefore, we used 0.1 of its width as a proxy to calculate the pylon's diameter ( $A_{lost,i,c,pl} = \sum_j \pi \cdot (0.5 \cdot (ROW_{i,b,pl} \cdot 0.1))^2$ ).  $A_{new}$  was then computed accordingly.

Using the resistance values, we calculated the least-cost distance ( $w$ ) between each pair of habitat patches ( $m, n$ ). Since the construction of the rights-of-way converts forests to open habitats, forested pixels with power lines were considered part of open habitat patches. A matrix was created encompassing all the patches of habitat type  $c$  within landscape region  $j$ . A patch could represent either a single pixel or a group of neighboring pixels. For every pair of patches, we measured the distance traveled through the pixels and multiplied it by the resistance ( $r$ ) values of the species of group  $k$  of taxon  $g$  (equation (6)). While we expect a species would take the shortest way to travel from patch to patch, we also assume it will favor going through pixels with lower resistance values, i.e. suitable habitat.

$$w_{k,g,c,j,mn,pl} = \sum d_{i,k,g,c,j,mn,pl} \cdot r_{i,k,g,c,j,pl} \quad (6)$$

By dividing the least-cost distance ( $w$ ) between every pair of patches ( $m, n$ ) by the median dispersal distance ( $\alpha$ ) of the species of group  $k$  of taxon  $g$  in habitat  $c$  within landscape region  $j$ , we generated a dispersal probability (equation (7))

$$p_{k,g,c,j,mn,pl} = e^{-w_{k,g,c,j,mn,pl} / \alpha_{k,g,c,j}} \quad (7)$$

Finally, the ECA was calculated by the number and size ( $a$ ) of every pair of habitat patches ( $m, n$ ) and by the dispersal probability ( $p$ ) of species of group  $k$  of taxon  $g$  to travel between these patches, which resulted from the construction of power lines type  $pl$  (equation (8))

$$ECA_{k,g,c,j,pl} = \left( \sum_{m,n} a_{c,j,m,pl} \cdot a_{c,j,n,pl} \cdot p_{k,g,c,j,mn,pl} \right)^{0.5} \quad (8)$$

### 2.2.2. Characterization factors

The collision and electrocution PDFs, which were calculated per pixel  $i$ , were summed per landscape region. Then, per impact pathway  $X$ , the PDF values were weighted based on the number of species in each species group  $k$  of taxon  $g$  and the total number of all species of taxon  $g$ . The weighted PDFs were aggregated per taxon group  $g$ . We extracted and summed the PDFs per Norwegian pricing area (PA). To aggregate the PDFs from landscape regions to pricing areas, we weighted them by their proportional area size ( $A$ ) within the pricing areas (equation (9))

$$PDF(X)_{g,PA,pl} = \sum_j PDF(X)_{g,j,pl} \cdot \frac{A_{j,PA}}{A_s} \quad (9)$$

The PDFs were divided by the total annual kWh electricity ( $E$ ) production or consumption for 2022 in each pricing area to derive the characterization factors (equation (10))

$$CF(X)_{PA,pl} = \frac{\sum PDF(X)_{k,g,PA,pl}}{E_{PA,pl}} \quad (10)$$

The characterization factors represent the impact of producing or consuming one kWh of electricity for the impact pathway  $X$ . Each impact pathway  $X$  was quantified separately for each power line type. Electrocutation, however, was calculated only for distribution lines because we assumed birds are electrocuted primarily by distribution lines, as discussed previously. Impacts caused by transmission lines were divided by the amount of electricity produced per pricing area. For the impact pathways of the low-voltage grid, the PDFs were divided by the electricity consumed per pricing area.

The LCIA data analysis was conducted in R Version 4.2.2 [47] in Rstudio 2022.07.2. The scripts are available in [57]. See also our data availability statement.

### 2.2.3. Sensitivity analyses

Sensitivity analyses have been performed to examine the variation in PDF values for each impact pathway and taxon across the different landscape regions and pricing areas.

For the habitat conversion and fragmentation model, 100 PDF calculations were computed based on the 100 random dispersal distances per species group  $k$  within taxon  $g$ . Similarly, 100 PDF calculations were generated for the collision model by 100 random CRP values, calculated for each bird group  $k$  based on data range and distribution. Finally, 200 random wingspans and pylon-use behavior values (100 values per factor) were conducted per bird group  $k$ , relying on the species group's distribution (beta distribution, in the case of the pylon-use behavior) and data range. From these values, 200 PDF values were created. The data for the collision and electrocution models were obtained from [26].

These calculations were conducted per landscape region, power line type, and species group  $k$  and were aggregated per taxon  $g$ . The PDF values were further aggregated to pricing areas based on the proportion of the area size of each landscape region within the pricing areas (equation (9)).

## 2.3. Data

### 2.3.1. Species data

We used the bird dataset compiled by [26], which encompasses body measurements (i.e. weight, wingspan, and wing area) and behavioral features (diet and foraging data). Weight and diet data of mammalian species were obtained from the EltonTraits 1.0 dataset [58]. To differentiate between carnivorous and non-carnivorous species, we classified carnivorous species as those whose diet consists mostly of meat (i.e. mammals and birds, reptiles and amphibians, unknown vertebrates, and scavengers). Non-carnivorous species were classified as primarily consuming invertebrates and plants (i.e. fruits, nectars, seeds, and other plant parts). Bird species lacking diet data (approximately 14%) received the median diet value of their group  $k$ . Natal dispersal distances were calculated per species based on its weight, home range, and natal dispersal distance, as explained in [27] (see supporting information 1, table S1).

For every species group  $k$  within the taxon  $g$ , we computed 100 randomly selected dispersal distances, encompassing the range of dispersal values observed for the species and aligned with their respective distribution. Subsequently, each dispersal distance value was employed to calculate the ECA and PDF values for the 45 landscape regions. Finally, we derived the mean PDF values for each species group  $k$  of taxon  $g$  per landscape region.

### 2.3.2. Land cover

We obtained a shapefile describing Norway's land cover for the year 2017 from [59]. The shapefile was rasterized to a resolution of 1 km<sup>2</sup>. We reclassified the land cover raster into two landscape types: forest and open habitats. The forest land cover class comprises about 40% of Norway's area. Open habitats were defined as agricultural, natural non-forest vegetation, peatland, and ice and snow. The urban, freshwater, ocean, and unknown land cover classes were excluded from the analysis (see supporting information 1, table S2).

We employed a two-step process to assess the impact of habitat conversion and fragmentation. First, we overlaid the forest land cover raster with the transmission and distribution rights-of-way, generating rasters with fragmented forests. Simultaneously, we used the power lines to mask the open habitat land cover. Pixels previously classified as forests but fragmented by the rights-of-way were converted into open habitat areas. It resulted in two versions of the original land cover raster: forest and open habitat. To calculate the ECA, we used the forest and open habitats rasters.

For the electrocution pathway, we downloaded forest cover density data for Norway at 10 m resolution from the EU Copernicus Land Monitoring Service [60] and aggregated them into one raster (1 km<sup>2</sup>).

### 2.3.3. Landscape regions

Ecoregions are often used in LCIA as a spatial component to address land use impacts on biodiversity [14, 37, 61]. They comprise large areas with similar species and communities [62]. However, only six ecoregions overlap Norway, indicating that while the scale of ecoregions may be suitable for global assessments, it is not

detailed enough for a regional analysis. Therefore, we used the 45 Norwegian landscape regions (see supporting information 2, figure S7). The landscape regions are classified by six components: major landforms, geological composition, water and waterways, vegetation, agricultural land use, and buildings and technical installations [63].

#### 2.3.4. The Norwegian electric grid

Power line data were obtained from [64]. The dataset categorizes power lines as central, regional, and distribution. Sections without kilovolts (kV) data, which covered less than one percent of the dataset, were excluded. We calculated a buffer for each power line section based on kV levels to account for the appropriate rights-of-way width. A 40 m width was created around lines of 420 kV, 35 m for 300 kV, 25–30 m for 132 kV [65], and 20 m for power lines with less than 132 kV [66]. To calculate the impacts of collision and habitat conversion and fragmentation, the buffered power lines were rasterized into a 1 km<sup>2</sup> raster. Each pixel indicated the total area size (km<sup>2</sup>) of the rights-of-way that crossed it. The diameter of each pylon was calculated based on the width of its rights-of-way. The total area size (km<sup>2</sup>) of all pylons within pixel *i* was summed, resulting in a raster (1 km<sup>2</sup>).

For the electrocution impact, a raster of pylon density of the distribution raster was generated for Norway (1 km<sup>2</sup>). The pylons were then counted per pixel. Next, voltage data from neighboring power lines were assigned to the pylons. The phase-to-phase distance was distributed based on table 6–1 in [67]. Finally, a raster (1 km<sup>2</sup>) was generated with the mean phase-to-phase distance of all pylons within each pixel.

#### 2.3.5. Norwegian electricity data

Electricity production data for 2022 were obtained from [68] per Norwegian pricing area. The data included daily megawatt data generated by hydropower, wind power, and burning waste. Annual electricity production was summed and converted to kWh. In addition, consumption data for 2022 per municipality were downloaded [69] and summed per pricing area.

## 3. Results

### 3.1. Mapping the distribution of species

We created distribution maps for 28 mammal species in Norway. All maps are provided in the data repository [57]. The performance of our distribution models was good across all species and species groups. Area Under the Curve (AUC) values for individual species ranged from 0.75 (*Mustela erminea*) to 0.98 (*Rattus norvegicus*). On average, the highest performance scores were obtained for ungulates (AUC = 0.92) and the lowest for carnivores (AUC = 0.85). Among the species distribution maps, mean annual temperature and elevation were the most important environmental variables. We observed some contributions of latitude, land cover, and distance to the sea. Terrain ruggedness index, temperature seasonality, precipitation, and precipitation seasonality had, on average, less effect on the models (see supporting information 1, table S3). Together with the bird species distribution maps created by [24], these maps were used as a base layer for the LCA analysis as they represent Norway's bird and mammal richness.

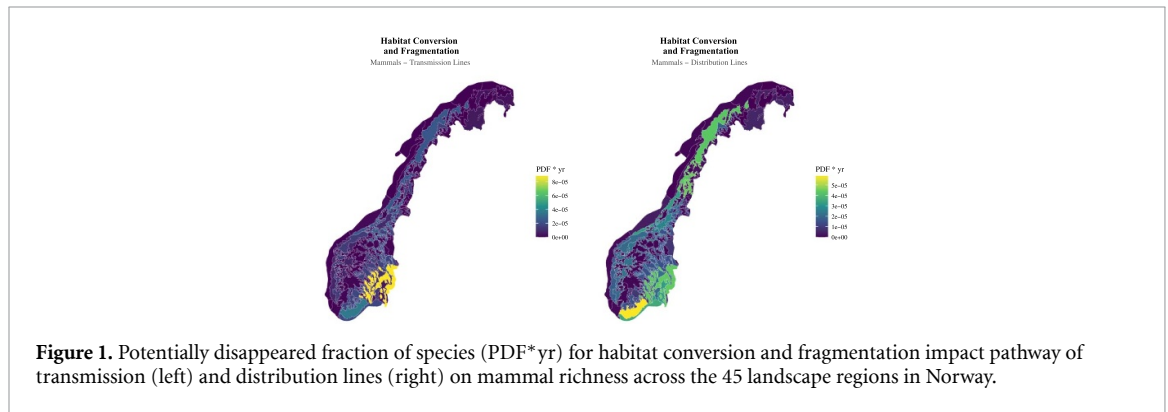
### 3.2. The impacts of power lines on the Norwegian biodiversity

The impact of collisions on bird richness from the distribution grid was slightly greater than that from the transmission lines. Similarly, despite the distribution lines having narrower rights-of-way compared to transmission lines, the local grid displayed higher PDF values due to habitat conversion and fragmentation in contrast to transmission lines. Furthermore, mammal diversity was more impacted by fragmentation as opposed to the impact on bird richness. Electrocution by distribution lines had a lesser effect on bird diversity than the other two impact pathways (see tables 2 and S4–S7 in supporting information 1).

**Table 2.** Annual potentially disappeared fraction of species (PDF\*yr) per impact pathway, taxon, and power line type in Norway.

| Impact Pathway                       | Taxon   | Transmission lines    | Distribution lines    |
|--------------------------------------|---------|-----------------------|-----------------------|
| Collision                            | Birds   | $2.75 \times 10^{-5}$ | $4.85 \times 10^{-5}$ |
| Electrocution                        | Birds   | —                     | $1.37 \times 10^{-6}$ |
| Habitat conversion and fragmentation | Birds   | $2.22 \times 10^{-5}$ | $4.71 \times 10^{-5}$ |
| Habitat conversion and fragmentation | Mammals | $4.17 \times 10^{-4}$ | $5.98 \times 10^{-4}$ |

The results suggest a higher impact in southern Norway and certain areas in the country's center and north. Distribution lines also posed a greater threat in the south and along Norway's south and western coastal areas (see figures S1–S3 in supporting information 2). As shown in figure 1, mammal richness was mostly impacted by habitat conversion and fragmentation resulting from constructing transmission lines in landscape regions characterized by coniferous forests. A landscape region dominated by coastal heaths experienced no impact due to the absence of high-voltage power lines. Notably, regions characterized by a subarctic climate and scarcity of forests remained unaffected by transmission and distribution lines.



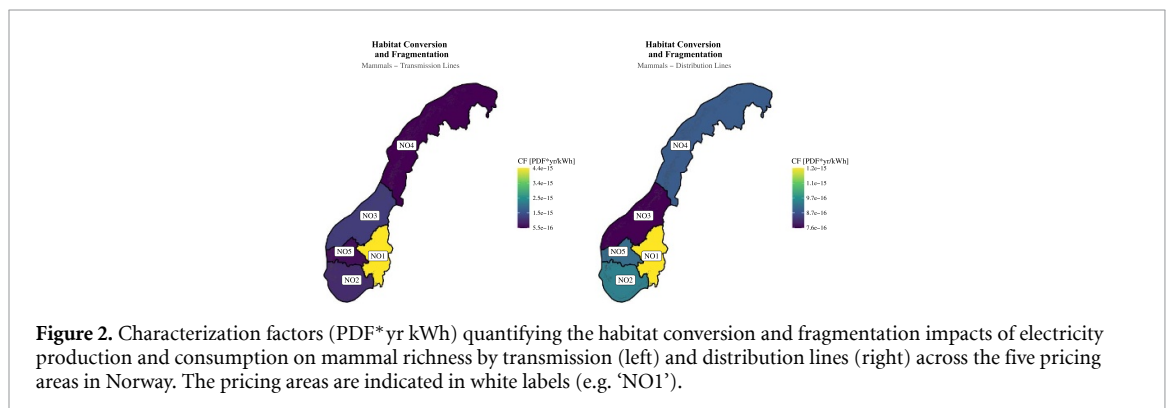
Distribution lines greatly impacted landscape regions with various forest types, e.g. spruce, pine, and birch. Conversely, regions not dominated by forests were less affected, i.e. areas comprised mostly of glacier landscapes or peatlands. Similar patterns were observed for the diversity of birds (see supporting information 1, tables S4 and S5).

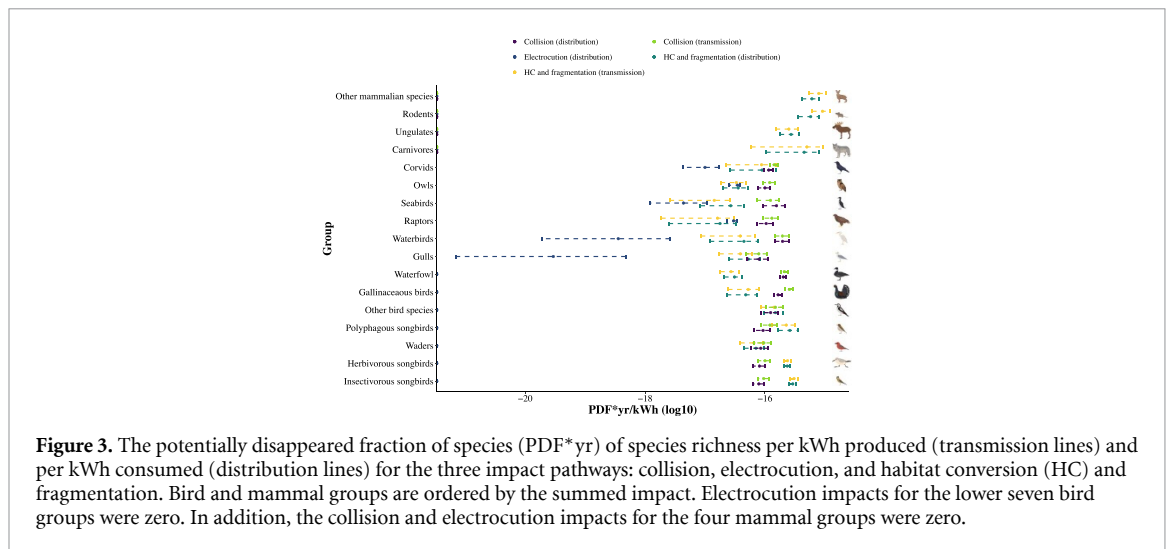
### 3.3. Electricity transmission between pricing areas and its impact on species richness

We developed 35 characterization factors for the taxon groups of mammals and birds. These characterization factors present the efficiency of electricity transmission within the Norwegian pricing areas regarding their impacts on species richness. They indicate impacts that vary over four orders of magnitude. The transmission of electricity by high-voltage power lines was least efficient due to habitat conversion and fragmentation ( $3.77 \times 10^{-16}$  PDF\*yr kWh for birds and  $7.77 \times 10^{-15}$  PDF\*yr kWh for mammals) in comparison to the collision of birds ( $4.01 \times 10^{-16}$  PDF\*yr kWh). The same pattern applies to the distribution grid, where habitat conversion and fragmentation have the least efficiency ( $3.29 \times 10^{-16}$  PDF\*yr kWh for birds and  $4.69 \times 10^{-15}$  PDF\*yr kWh for mammals), followed by collision ( $3.04 \times 10^{-16}$  PDF\*yr kWh) and electrocution ( $9.44 \times 10^{-18}$  PDF\*yr kWh) of birds.

Figures 2 and S4–S6 in supporting information 2 show that the impact pathways and the power line type have different effects across the pricing areas.

For instance, the habitat conversion and fragmentation characterization factors show that the distribution network has a higher impact on bird richness in pricing areas five, two, and one. In contrast, the transmission lines impacted pricing areas one and three. The latter trend holds for both mammal and bird diversity.





Pricing areas one, three, and five had the highest values for the collision impact pathway for transmission and distribution lines. The efficiency of electricity transmission regarding electrocution indicated a lower effect in pricing area four, whereas pricing areas one and five displayed higher values (see supporting information 1, table S8).

### 3.4. The impacts of power lines on bird and mammal richness

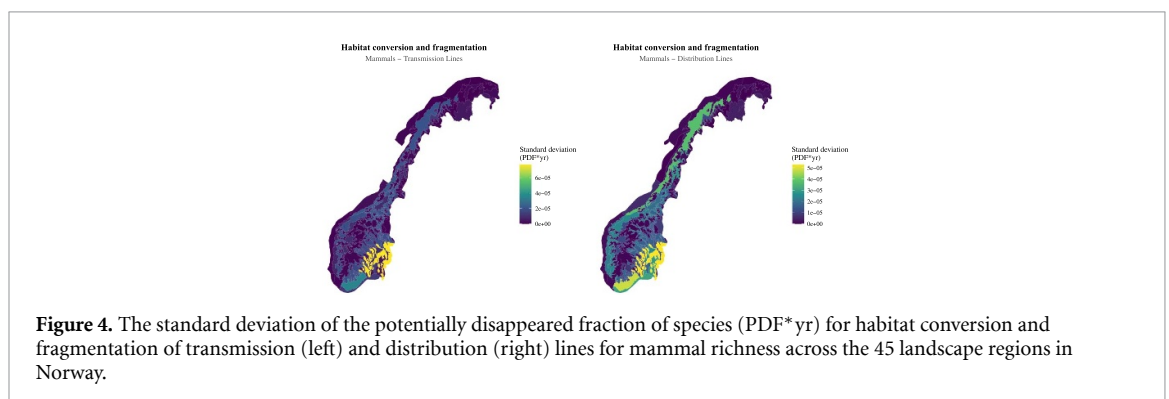
The three impact pathways impacted bird and mammal richness differently across subgroups. Habitat conversion and fragmentation had the highest impact among the three and affected mammals more than birds, as indicated in figure 3. Other mammalian species and rodents had higher PDF values than ungulates and carnivores. In contrast, songbirds and other bird species were most affected by habitat conversion and fragmentation among the bird groups. Collision had a higher impact on birds than electrocution, with waterfowl, water birds, seabirds, and gallinaceous birds being the most vulnerable. Electrocutation affected mostly owls and raptors, followed by corvids and seabirds. In general, The PDF values of the distribution network were higher than the transmission grid (see supporting information 1, tables S9 and S10).

### 3.5. Sensitivity analyses

Spatial variation in PDF values was observed across different landscape regions, with notable variations in regions 3, 5, 7, and 32. In contrast, lower variation was detected in regions 16, 17, 44, and 45 (see tables S11 and S12 in supporting information 1 and figures S8–S17 in supporting information 2).

The results for habitat conversion and fragmentation varied across landscape regions, with greater variability observed for mammals compared to birds. Additionally, higher variation was noted for distribution lines compared to transmission lines, particularly for the impacts on mammals (see figure 4).

Among the five Norwegian pricing areas, PDF values exhibited the most variation in pricing area one across all the impact pathways, occasionally surpassed by pricing area two. In contrast, collision and electrocution results varied the least in pricing area five, while pricing area four showed lower variation in PDF values for the habitat conversion and fragmentation models (see table S13 in supporting information 1 and figures S18–S21 in supporting information 2).



Finally, the PDF values for habitat conversion and fragmentation models also varied across mammal and bird groups, with higher variation observed in bird groups. Within bird groups, polyphagous songbirds, other bird species, and corvids showed the highest variation. Among the four mammal groups, carnivores exhibited the greatest variation (see figures S22 and S23 in supporting information 2).

## 4. Discussion

The regional characterization factors for the effects of power lines on bird and mammal richness in Norway cover three impact pathways: collision, electrocution, and habitat conversion and fragmentation. The impacts varied across taxon groups, Norwegian landscape regions, and pricing areas. This stresses the importance of regionalization in LCA [70, 71], as these impacts affect species richness differently, depending on the geographic distribution of the species, the characterizations of the landscape regions, and the locations of power lines within each region and pricing area.

The regional characterization factors were calculated separately for transmission and distribution lines. Despite distribution lines having narrower rights-of-way than transmission lines, their overall impact was greater. In Norway, the extent of the distribution network is three times larger than the transmission grid. So, even if the impact of the low-voltage grid may be smaller on a section-by-section basis, it can accumulate significantly at a national level.

In general, transmission lines and their impacts on biodiversity receive much more attention in the literature [6]. However, our findings stress the importance of considering the distribution network when planning mitigation measures to reduce the impacts of power lines on biodiversity. Moreover, collision and electrocution have been extensively documented as the main impacts of power lines on wildlife [7, 8]. However, our results suggest that habitat conversion and fragmentation impact bird richness more than collision and electrocution.

Transmission lines were excluded from the electrocution impact pathway since only a few birds were electrocuted on high-voltage lines in Norway, according to Statnett's unpublished dataset. While the dataset indicates that most electrocutions occur on distribution lines, the records were not collected systematically and were primarily based on short-circuit registrations. Although the dataset might not fully represent the situation in Norway, we believe that including transmission lines would likely result in overestimating the impact. Moreover, other studies have also shown that birds are more frequently electrocuted on distribution lines compared to transmission lines [40, 72, 73].

We quantified the biodiversity impacts of power lines while focusing on mammal and bird species, as they are well-studied taxa in the context of power lines, particularly birds [7, 8]. Gilad *et al* [74] quantified the regional and global habitat loss impacts of power lines for these two taxonomic groups. Notably, in the case of Norway, the regional characterization factors in their study were two orders of magnitude smaller than what we present in this paper. The differences in the methodology can explain this gap. As [27] pointed out, when a landscape becomes highly fragmented, characterization factors calculated by a SHR model will be higher than those computed by countryside-SAR models, as utilized by [74]. Furthermore, it is worth noting that the data used in [74] had a global scope, leading to coarser resolution and potentially lower data quality than the national data used in this study. Nonetheless, global characterization factors can be compared across different spatial areas. However, our regional characterization factors for collision, electrocution, and habitat conversion and fragmentation represent regional effects in Norway. Hence, the reduction in species richness is limited to the Norwegian pricing areas and cannot be compared with other countries. It is possible to adapt the characterization factors to a global scale with the Global Extinction Probabilities [61].

The study by [74] also suggests that habitat loss affected bird richness more than mammals. In contrast, our findings indicate that the habitat conversion and fragmentation impact pathway affect mammal richness more than bird richness. While both taxonomic groups are strongly affected by habitat loss, birds, which can fly through a hostile matrix, are less susceptible to fragmentation than mammals [75]. It appears that the ability to fly can reduce the negative effect of fragmentation [50, 76].

Bats were excluded from our analysis due to a lack of available data, but they are known victims of power lines [43]. Similarly to birds, larger bats may be more at risk of getting electrocuted, as shown in a recent study that recorded the electrocution of tropical bats by power lines [77]. Although the loss and fragmentation of forests can negatively impact bat populations [78, 79], some studies showed that canopy gaps can increase bat activity [80, 81]. This is only one example of the positive effects of rights-of-way on species. Converting a closed forest to an open area impacts forest-dwelling species but may benefit other species [7]. Pollinators, for instance, are attracted to power line corridors, which provide valuable habitats [82–85]. Some even claim that using power lines for perching and nesting is beneficial for birds alongside the risk of collision and electrocution [86–88]. Furthermore, some studies show that ungulates avoid

rights-of-way [89, 90]. Still, others suggest that the newly formed corridors provide foraging opportunities to species, e.g. moose (*Alces alces*) and white-tailed deer (*Odocoileus virginianus*) [7, 11].

The LCIA framework offers a comprehensive perspective on the life cycle of a product and the variety of environmental impacts it creates. Nevertheless, it comes at a price: simplified, generalized models [91]. Moreover, the framework primarily focuses on quantifying negative impacts [92, 93]. Ecosystems, however, are not simple. They are complex, interactive, and dynamic. Therefore, our models, similarly to existing LCIA models, are limited in their capability to address biodiversity impacts fully [94–96]. For instance, our assessment of the habitat conversion and fragmentation impact relies on species habitat specialization and the dispersal distance of each subgroup  $k$ . So, species that live in forests with a low dispersal probability will be more affected. However, other factors such as litter size and lifespan may also play a role in species' sensitivity to fragmentation [97].

Based on our results, other mammalian species and rodents were the most affected subgroups. Several studies show that the species richness of small mammals in rights-of-ways is higher compared to the undisturbed forested habitat [98–101], suggesting that this species group is less affected by fragmentation. Nonetheless, most species recorded within the power line corridors were species that favored open habitats, while power lines seem to constrain the movement of forest-dwelling species [101]. Moreover [50], claim that although the size of small mammal populations may decrease after fragmentation, their density is higher than that of large mammals so that they can recover faster.

Medium-sized mammals tend to avoid linear clearings and prefer forests [102–104], which could explain the higher impact for the subgroup other mammalian species that consists of the European hedgehog (*Erinaceus europaeus*), the Eurasian water shrew (*Neomys fodiens*), and the mountain hare (*Lepus timidus*).

Power lines may not pose a barrier for ungulates [105, 106], but linear clearings can negatively affect ungulate populations due to habitat change and increased predation [107, 108]. Although larger mammals are often more affected by habitat loss and fragmentation [50, 97, 109, 110], several studies show that carnivores are attracted to linear clearings and select them for their travel patterns [102, 104, 111]. For example, wolves (*Canis lupus*) [112] and black bears (*Ursus americanus*) [113].

Collision and electrocution affect bird groups differently, depending on the species morphological and behavioral characteristics, as discussed in [26].

Grouping individual species into species groups and taxa can introduce uncertainties. This is because characteristics specific to each species, such as dispersal distance, probability of collision risk, wingspan, and pylon-use behavior, are averaged across bird and mammal groups. This effect was evident in our sensitivity analyses, where PDF values showed variation across different species groups and impact pathways. The sensitivity analyses also revealed spatial variations across different landscape regions and pricing areas, with notable variability observed in Southeast Norway. However, the overall fluctuation in the PDF results was relatively minor, as the values largely remained within the same order of magnitude.

Our regional habitat conversion and fragmentation models are based on a global approach [27]. Nevertheless, we induced several substantial changes derived from working at a local scale. Instead of using IUCN or BirdLife range maps that assume equal species presence across large geographic areas, we used species distribution maps. These maps offer a more accurate likelihood of the potential distribution of species, as they can represent habitat suitability.

The global models developed characterization factors for terrestrial ecoregions, the recommended spatial unit to quantify land-use impacts on biodiversity in LCIA [114]. However, ecoregions were insufficient to assess the effects of power lines on biodiversity in Norway because their coverage within the country was too coarse. The Norwegian landscape regions offered a good alternative. While they differ from ecoregions, which focus solely on biogeographical features before human-induced changes, the landscape regions provide a comparable spatial unit, as they capture the characteristics of each landscape region. Much like ecoregions, the landscape regions are defined by landscape characterization rather than administrative boundaries. Moreover, both units represent diverse landscapes at a regional scale [63, 115].

The global characterization factors cover four anthropogenic land-cover types: urban, cropland, pasture, and forestry. Our study focused on forest and open landscapes. In the context of power lines, the impact of habitat conversion and fragmentation primarily results from tree removal during power line construction. Consequently, we considered non-forest habitat types (i.e. agricultural fields, natural non-forest vegetation, peatland, and ice and snow) as a homogeneous open habitat, assuming only minimal habitat loss due to pylon construction. Since we focus on terrestrial impacts, we excluded ocean and freshwater land cover classes from our analysis. Urban areas were also omitted, as our models assessed the effects of power lines on forests and open landscapes. Furthermore, we used the species distribution maps to compute resistance values instead of deriving them by evaluating species' affinity for land and matrix types. This method generated a regional resistance matrix based on habitat suitability and species presence, offering a more accurate representation of species movement probabilities between habitat patches.

To assess the effects of habitat conversion and fragmentation, [27] conducted a comparative analysis between two land cover maps: a reference state prior to human activities and a current state. Their study evaluated land-use changes that would occur across large areas. Our models focused on the impact of power lines, which would only influence a limited portion of the landscape, namely, where the rights-of-way are built. Consequently, we needed to modify the methodology to prevent overestimating the impact. To achieve this, we compared the ECA with the changes in the resistance layers, representing the species' ability to move within the landscape.

Lastly, rather than using a resolution of 5' (9 km) as [27], we ran our habitat conversion and fragmentation model at a finer resolution (1 km<sup>2</sup>). Spatial resolution plays an important role in our models but is also a significant hindrance. Our habitat conversion and fragmentation model examines the connectivity between patches. Ideally, we would use a small scale (e.g. 10 m) to obtain highly accurate information about landscapes fragmented by power line corridors, which range in width between 20–40 m [65, 66]. This would also enable more in-depth analysis of subgroups with dispersal distances smaller than 1 km, such as rodents and other mammalian species, which were limited by the pixel size.

However, we selected a 1 km<sup>2</sup> resolution for several reasons. Firstly, although our primary goal was to adapt and develop models for quantifying the impacts of power lines on biodiversity, regionalized LCIA models typically offer global coverage [116]. However, access to high-resolution data on a global scale may not always be feasible. Therefore, we chose to create models using local data at the current scale, enabling easy adjustments with global data. Although our methodology focuses on Norway, it is not limited to this country. Our codes can be downloaded to generate species distribution maps for any country or region based on available GBIF records. Moreover, global land cover products are freely accessible in 100 m resolution [117], as well as a global dataset of transmission and distribution lines [118].

Secondly, the species distribution maps were the baseline of our models. The resolution for these maps was decided by the availability of input data (1 km<sup>2</sup>). Aggregating the species distribution maps to achieve a higher resolution may result in data loss.

Thirdly, running our models is computationally intensive, even at the selected scale. While running the model on very fine-resolution data is possible, a higher level of resolution may not inherently translate to increased accuracy. Therefore, we decided to compromise between accurately representing the landscape and ensuring that the models were computationally feasible.

Finally, our models only address the operational phase, but the construction phase may induce short-term disturbance for species such as reindeer (*Rangifer tarandus*) [106, 119].

## 5. Conclusions

This study adapted LCIA models to quantify the three main impacts of electricity transmission on mammal and bird richness in Norway: habitat conversion and fragmentation, collision, and electrocution. These landscape-scale models offer insights into which species groups and geographic regions are most affected by power lines in Norway. About 140 billion NOK are allocated for investments in the Norwegian grid until 2029 [120]. Our results show that habitat change has the highest effect on the diversity of both mammals and birds. Therefore, further construction of power lines must be planned carefully to mitigate the impact on local species. This is particularly true for the distribution grid, which often affects species richness greatly than transmission lines.

Notably, the sensitivity analyses revealed that the greatest level of uncertainty was linked to the impact pathway of habitat conversion and fragmentation. This uncertainty can be attributed to the substantial variation in dispersal distances across different species groups. Additionally, the uncertainty is greater due to the consideration of two taxa, as opposed to a singular focus on bird species, which was the approach taken for the impact pathways of collision and electrocution.

Quantifying the biodiversity impacts of power lines in Norway is vital for assessing and promoting sustainable energy systems. Integrating them into existing Norwegian models that evaluate the environmental impacts of electricity generation from hydropower [21, 22] and wind power [24] can offer a holistic assessment—from energy production through transmission and to consumption.

By obtaining a comprehensive understanding of the potential effects of power systems on biodiversity, policymakers can facilitate strategic planning and promotion of renewable energy while minimizing its impacts on biodiversity, thus contributing to sustainable energy development.

## Data availability statement

The data that support the findings of this study are openly available at the following URL: <https://zenodo.org/doi/10.5281/zenodo.10067068>.

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