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Dafna Gilad

Modelling biodiversity impacts of renewable energy systems in Norway

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
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Preface

The thesis has been submitted to the Faculty of Engineering Science in partial fulfilment of the degree of Philosophiae Doctor. This work was carried out in the Industrial Ecology Programme and the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, from 2021 to 2024.

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Dafna Gilad,
Trondheim, March 2024

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Abstract

Global renewable energy production must triple by 2030 to mitigate global warming. This requires a considerable expansion of global energy facilities and electric grids.

Norway is well-positioned for this energy transition, with 98% of its electricity generated from renewable sources like hydropower and wind. Its climate plan aims to cut emissions by half by 2030 through electrification and increased electricity production. However, while the Norwegian government is responsible for fulfilling its climate goals, it is also committed to protecting nature. The development of hydropower and wind farms can disturb wildlife and pose risks to biodiversity through habitat loss and fragmentation, while turbines can cause species mortality. Moreover, power line construction alters and fragments habitats and endangers bird populations through collision and electrocution.

Life cycle assessment is a valuable instrument for assessing the trade-offs between renewable energy expansion and biodiversity conservation. While existing life cycle impact assessment (LCIA) models cover biodiversity impacts related to electricity production, a gap exists in addressing impacts associated with electricity transmission.

This PhD thesis has two goals: (1) developing biodiversity LCIA models to quantify the impacts of power lines on Norwegian species richness, and (2) integrating existing models to analyse the biodiversity impacts of the Norwegian electricity system, including generation and transmission.

Chapter 2 introduces LCIA models that assess the impacts of power lines on bird richness due to collision and electrocution. In Chapter 3, existing LCIA models are adapted to quantify the effects of power lines on bird and mammal richness in Norway from habitat conversion and fragmentation. Overall, distribution lines had a greater impact on species richness, primarily affecting mammal diversity through habitat conversion and fragmentation, while bird richness is more influenced by collisions than electrocutions. Chapter 4 demonstrates the potential global application of these models, using global datasets to assess habitat loss impacts on bird and mammal diversity worldwide. Finally, Chapter 5 merges the newly developed biodiversity LCIA models with existing ones to comprehensively evaluate the current effects of the Norwegian electricity system on species richness. While hydropower electricity production emerged as the primary contributor to biodiversity impacts, the electric grid also significantly affects species richness.

As the energy transition unfolds, critical decisions must balance climate mitigation with preserving nature. The methodology outlined in this thesis offers an assessment approach towards a sustainable, environmentally friendly energy shift. It aims to ensure that the progress towards climate goals does not come at the expense of natural ecosystems.

Sammendrag

Den globale produksjonen av fornybar energi må tredobles innen 2030 for å begrense globaloppvarming. Dette krever en betydelig utbygging av globale energianlegg og strømnett.

Norge er godt posisjonert for denne energiomstillingen med 98% av elektrisiteten fra fornybare kilder som vann- og vindkraft. Norges klimaplan har som mål å halvere utslippene innen 2030 gjennom elektrifisering og økt strømproduksjon. Samtidig har den norske regjeringen forpliktet seg til å beskytte naturen. Utbygging av vann- og vindkraftverk kan nemlig forstyrre dyrelivet og utgjøre en risiko for det biologiske mangfoldet gjennom tap og fragmentering av leveområder, samtidig som turbiner kan føre til at arter dør. I tillegg kan bygging av kraftledninger endre og fragmentere habitater og utsette fuglebestander forkollisjons- og elektrokusjonsfare.

Livsløpsanalyser er et verdifullt verktøy for å vurdere avveiningene mellom utbygging av fornybar energi og bevaring av biologisk mangfold. Eksisterende modeller for livsløpskonsekvensanalyse (LCIA) dekker konsekvenser for biologisk mangfold i forbindelse med strømproduksjon, men er mangelfulle når det gjelder konsekvenser knyttet til kraftoverføring av elektrisitet.

Denne doktorgradsavhandlingen har to mål: (1) å utvikle LCIA-modeller for biologisk mangfold for å kvantifisere hvordan kraftledninger påvirker artsmangfoldet i Norge, og (2) å integrere eksisterende modeller for å analysere konsekvensene for biologisk mangfold av det norske kraftsystemet, inkludert produksjon og overføring.

Kapittel 2 introduserer LCIA-modeller som vurderer kraftledningers påvirkning på fuglelivet som følge av kollisjoner og elektrokusjon. I kapittel 3 tilpasses eksisterende LCIA-modeller for å kvantifisere effekten av kraftledninger på mangfoldet av fugler og pattedyr i Norge som følge av habitatkonvertering og fragmentering. Distribusjonslinjer har totalt sett den største innvirkningen på artsrikdommen, hovedsakelig ved å påvirke pattedyrmangfoldet gjennom habitatkonvertering og fragmentering. Samtidig er fuglenes artsrikdom i større grad påvirket av kollisjoner enn av elektrokusjon. Kapittel 4 viser at det er mulig å bruke disse modellene globalt for å vurdere hvordan tap av leveområder påvirker mangfoldet av fugler og pattedyr over hele verden. Kapittel 5 forbinder de nyutviklede LCIA-modellene for biologisk mangfold med eksisterende modeller for å evaluere de nåværende effektene av det norske kraftsystemet på artsmangfoldet. Vannkraftproduksjon viser seg å ha størst påvirkning på det biologiske mangfoldet, samtidig påvirker også strømnettet artsrikdommen i betydelig grad.

Underveis i energiomstillingen, må beslutninger balansere klimatiltak og naturvern. Metoden som skisseres i denne avhandlingen tilbyr en vurderingsmetode for et bærekraftig og miljøvennlig energiskifte. Målet er å sikre at veien mot klimamålene ikke går på bekostning av naturlige økosystemer.

Publications

This thesis is based on four publications:

Gilad, D., May, R., Stokke, B. G., & Verones, F. (2024). Between the Lines: Life Cycle Impact Assessment Models of Collision and Electrocution Impacts of Power Lines on Bird Diversity in Norway. *The Journal of Industrial Ecology,* 1–13. https://doi.org/10.1111/jiec.13488
Author contribution: Study design, data collection, modelling, writing.

Gilad, D., Borgelt, J., May, R., & Verones, F. (in review). Biodiversity on the Line: Life Cycle Impact Assessment of Power Lines on Species Richness. *The Journal of Environmental Research: Infrastructure and Sustainability.*
Author contribution: Study design, modelling, writing.

Gilad, D., May, R., & Verones, F. (2023). Quantifying Global Powerlines Impacts on Birds and Mammals. In L. Denney & N. Geagea Pupa (Eds.), *Environmental Concerns in Rights-of-Way Management 13th International Symposium* (pp. 37–72). Pique Publishing, Inc.
Author contribution: Study design, data collection, modelling, writing.

Gilad, D., Borgelt, J., May, R., Dorber, M., & Verones, F. (in review). Biodiversity Impacts of Norway's Renewable Electricity Grid. *The Journal of Cleaner Production.*
Author contribution: Study design, assisted in parts of the modelling, writing.

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1.

INTRODUCTION

The year 2023 emerged as the hottest year ever recorded (Copernicus, 2024). The global average temperatures of 2023 were steadily approaching the critical threshold of 1.5° degrees Celsius above pre-industrial levels (Copernicus, 2023c). This warming is primarily attributed to the emission of greenhouse gases resulting from human activities (IPCC, 2023), and its impacts are already manifesting through intensified global wildfire activity (Copernicus, 2023a), persistent heatwaves (Copernicus, 2023b; NASA, 2023) and increased occurrences of floodings (Copernicus, 2023b).
Since the energy sector contributes nearly 75% of global greenhouse gas emissions (Ritchie, 2020), there is a clear need for a rapid transition from fossil fuels to renewable sources (Shukla et al., 2022). Accordingly, the recent annual climate meeting of the United Nations (COP28) concluded "to transition away from fossil fuels" (COP28, 2023). This transition is underway. The global annual renewable capacity additions nearly doubled from 2022 to 2023 and are expected to continue to grow, paving the way for renewables to become the primary source of electricity by 2025 (IEA, 2024). Climate policies drive this change, as many governments are committed to net zero emissions by promoting renewable energy production (IEA, 2023).
One nation undertaking climate action measures is Norway. In alignment with global trends, Norway has witnessed a rise in annual average temperatures, particularly in recent decades (NKSS, 2015). The country is also experiencing extreme weather events, including heatwaves (MET, 2022) and heavy rainfall (KMD, 2023). For instance, Storm Hans hit Norway in August 2023, triggering floods and landslides (Bryant, 2023). This was followed by intense snowfall and exceptionally cold temperatures in southern Norway in January 2024 (Bryant, 2024).
Climate change and its mitigation are prominent concerns in Norway. However, while the Norwegian government is committed to reducing its carbon footprint and promoting renewable energy production to meet its goals under the Paris Agreement, Norway also participates in international biodiversity initiatives such as the Kunming-Montreal Global Biodiversity Framework (NOU 2023:25, 2023; NOU 2024:2, 2024). The expansion of renewable energy infrastructure for electricity production, including the construction of new power lines, raises concern for Norway's natural landscapes. Moreover, the threat low-carbon technologies pose to biodiversity, such as hydropower and wind power, extends beyond habitat loss.

1.1 Norway's climate policy

Norway published its climate action plan for 2021-2030 in January 2021 (KMD, 2021). The climate action plan introduced two ambitious targets to contribute to the Paris Agreement: a reduction of 50-55% and 90-95% of greenhouse gas emissions by 2030 and 2050, compared to the emission levels in 1990 (KMD, 2021). The latter goal aims to meet international requirements and underscore Norway's commitment to transforming into a low-emission society (KMD, 2021; NOU 2023:25, 2023; OED, 2021). The Norwegian climate action plan outlines a range of policy instruments and measures to mitigate emissions across all sectors (see Figure 1.1), promoting a climate-friendly society (KMD, 2021; NOU 2023:25, 2023). Examples of such measures include raising taxes (i.e., carbon tax), employing stricter climate-related requirements in public procurement processes, supporting research of new technologies, improving spatial transport planning, and expanding biofuel use (KMD, 2021).

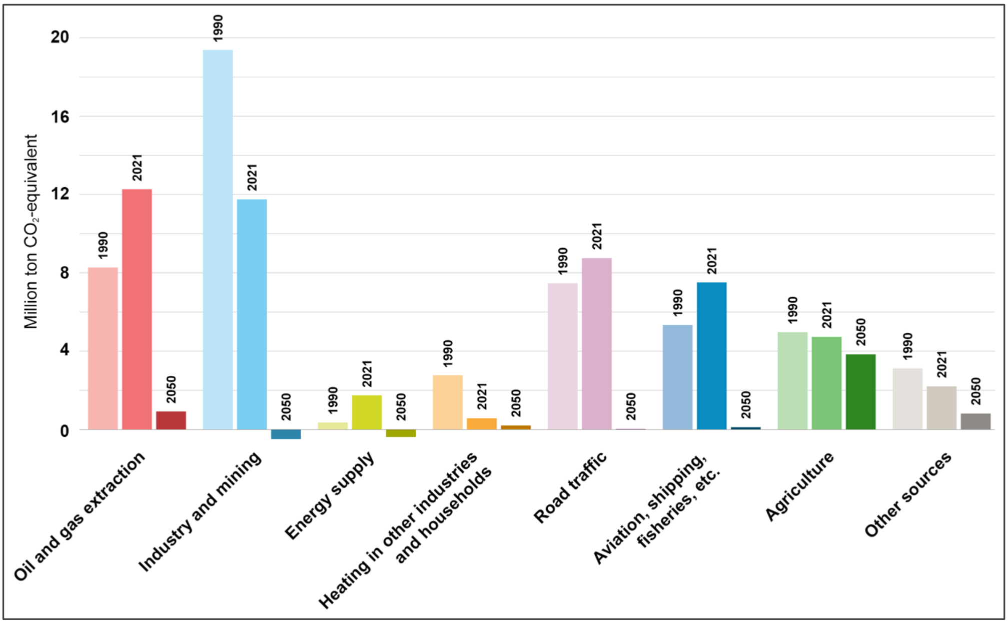

Figure 1.1. Comparison between historic emission levels in 1990 and 2021 and expected emission levels in 2050 across the main Norwegian sectors. Emissions from forestry and land use are not included. Source: Figures 3.3 and 3.10 in NOU 2023:25 (2023), modified.

The Norwegian government promotes electrification across numerous sectors to achieve the country's ambitious climate targets (KMD, 2021). While a fast shift to electrification is crucial for meeting climate goals by reducing dependence on fossil fuels (IEA, 2023), Norway is already at a good starting point: electricity constituted 42% of its total final energy consumption in 2022 (NVE, 2023e). Nevertheless, the country still relies heavily on fossil fuels, particularly in the petroleum, industry, and transport sectors (see Figure 1.2). Therefore, prioritising electrification in these sectors is a key measure in reducing emissions (NOU 2023:25, 2023; OED, 2021).

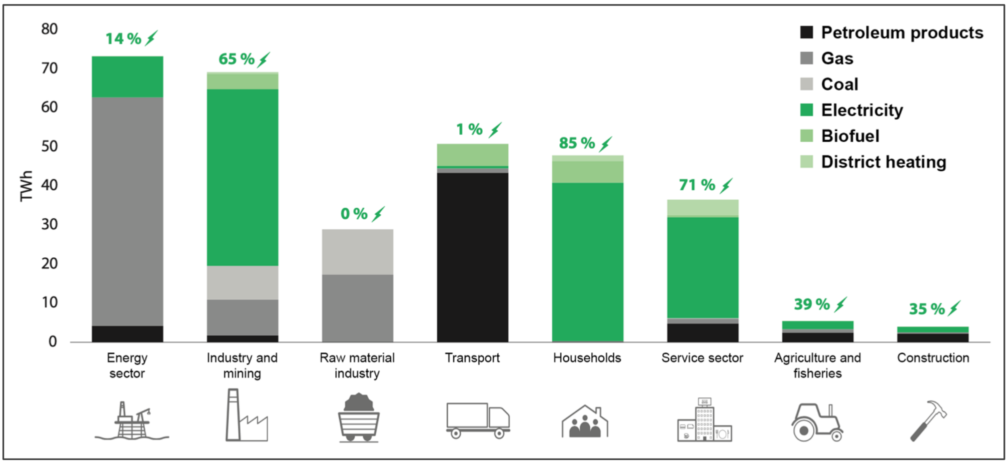

Figure 1.2. Energy consumption by energy source across sectors in Norway in 2019. The green percentage at the top of the bars indicates the electrification share per sector. Source: Figure 3.5 in OED (2021), modified.

However, implementing cross-sector electrification will result in a growth in electricity demand. The electrification of the industrial and petroleum sectors alone is expected to increase electricity consumption by 24 terawatt-hours (TWh) by 2030 (NOU 2023:3, 2023) and between 40 and 60 TWh by 2050 (Statnett, 2023b). Consequently, Norway must substantially expand its electricity production from renewable sources to meet these growing demands (KMD, 2021; NOU 2023:3, 2023). The need for a rapid energy transition is strongly emphasised in the recent report "More of everything – faster" by the Norwegian Energy Commission (NOU 2023:3, 2023).

1.2 The electricity system in Norway

The backbone of today's Norwegian electricity system is based on renewable sources. Hydropower and onshore wind power contribute 98% to Norway's electricity production (approximately 88% and 10% in 2022, respectively) (SSB, 2023a). The remaining electricity (1.63% in 2022) originates from district heating (SSB, 2023a), based on waste, biofuel, electricity, and fossil fuels (SSB, 2023b). Solar power has a minimal contribution to Norway's electricity production, as solar power cells are primarily installed on rooftops (NOU 2023:3, 2023; NVE, 2023b).

Hydropower

In Norway, a network of 1,781 hydropower plants produces an annual average of approximately 137.2 TWh (NVE, 2023g). The development of hydropower dates back to the late 19th century and peaked in the 1950s-1980s with the construction of large-scale hydropower projects (Tellefsen et al., 2020), which nowadays contribute the most to Norway's electricity production (NOU 2023:3, 2023). The mountainous regions in southern and northern Norway host the majority of the hydropower plants and reservoirs (NOU 2023:3, 2023). The hydropower plants are weather-dependent: during a wet season, they can produce approximately 76-80 TWh more than during a dry season (NOU 2023:3, 2023; NVE, 2020). On the other hand, the Norwegian reservoirs store an electricity capacity of 87.4 TWh (NVE, 2023d). The reservoirs, therefore, offer flexibility, enabling the release of water to produce electricity when needed (NVE, 2023c).

Looking ahead to the next few decades, Norway anticipates an additional eight to 12 TWh in electricity generation through the expansion of existing hydropower plants, construction of new facilities, installation of new turbines, and increased water inflows (NVE, 2023b; Statnett, 2023b). The construction of new large-scale hydropower plants is currently not possible in Norway due to social opposition driven by concerns for nature (NOU 2023:3, 2023; Tellefsen et al., 2020).

Wind power

Over the past two decades, 65 onshore wind power plants have been built in Norway, producing 14.7 TWh in 2022 (NVE, 2023a). Most wind turbines are located along the coast in southwest and central Norway (NOU 2023:3, 2023; NVE, 2020a). In 2019, the Norwegian Water Resources and Energy Directorate (Noregs vassdrags- og energidirektorat; NVE) proposed a new national framework for the development of wind power (NOU 2023:3, 2023; OED, 2020), specifying suitable areas for new wind farms (OED, 2020). This initiative encountered social opposition, leading to a pause in the concession process for new power plants (NOU 2023:3, 2023). Three years later, the Norwegian government revived the process for new onshore wind power projects. Yet, due to the controversial nature of wind power in Norway (NOU 2023:3, 2023; NVE, 2023b; Tellefsen et al., 2020), the projection of onshore wind power development remains conservative: by 2040, electricity production from onshore wind power is expected to increase by four to six additional TWh. In contrast, offshore wind power is expected to generate 29-33 additional TWh by 2040 (NVE, 2023b; Statnett, 2023b). Although there are several operational floating wind power plants in Norway, offshore wind power development remains in its early stages today (NOU 2023:3, 2023).

The grid system

Norway's power grid consists of three types of power lines: transmission, regional, and distribution. Transmission lines, spanning 13,000 km, facilitate the transfer of electricity between regions at voltage levels ranging from 300 to 420 kilovolts (kV) and are operated by Statnett, the country's transmission system operator. Regional lines, totalling 19,000 km, are owned by regional companies and transmit electricity within regions through 33 to 132 kV grid lines. Distribution lines connect consumers to electricity with a maximum voltage of 22 kV. The distribution grid is owned by regional or local companies and is the most extensive network: 320,000 km long. Newly built distribution lines are installed underground, whereas regional and central lines are typically built as overhead power lines (NOU 2022:6, 2022).

With the anticipated growth in the electricity demand (NOU 2023:3, 2023; Statnett, 2023c, 2023b), more customers request connections to the Norwegian grid (Statnett, 2023c, 2023a). Moreover, the planned increase in electricity production would require future power plants to be linked to the transmission grid (Statnett, 2023c). Therefore, the electric network must be upgraded and expanded (NOU 2022:6, 2022; Statnett, 2023c, 2023a), particularly in western, eastern, and central Norway, to strengthen the network that links the north and south (Statnett, 2023c, 2023a).

Future development plans for the Norwegian grid include upgrading existing power lines (e.g., from 300 kV to 420 kV) and constructing new power lines to increase transmission capacity (Statnett, 2023a). Acknowledging the need for grid expansion, the government eased the concession process for power lines, facilitating faster progress in building new power lines (OED, 2023).

Pricing areas

When electricity demand is higher than the capacity of electricity that can be transmitted, bottlenecks occur between areas with surpluses and deficits (NVE, 2020b; Statnett, 2022). Given Norway's uneven spatial distribution of production and consumption, these bottlenecks occur nationwide. The established solution to address this was implementing pricing areas (NOU 2022:6, 2022; Statnett, 2022). Norway has been divided into five pricing areas based on transmission capacity (Statnett, 2022). Generally, NO2 and NO4 are the major electricity producers across the regions (see Figure 1.3). High electricity consumption occurs in NO2 and NO1 (including Oslo). The latter produces the least amount of electricity (ENTSO-E, 2023).

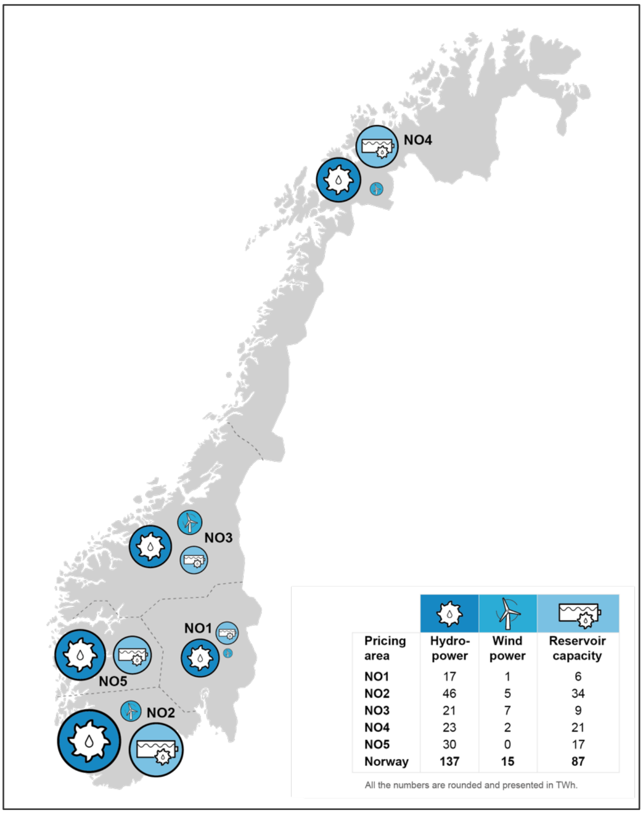

Figure 1.3. Electricity production across the five Norwegian pricing areas and per renewable energy source in 2021. The size of the circles indicates the share of electricity production across Norway. Source: (OED, 2022), modified.

1.3 Norway's nature

On a global scale, Norway is not renowned for its rich species diversity. Since the country was covered in ice around 10,000 years ago, many of its current species migrated to Norway after the ice age, resulting in a relatively low number of endemic species (KMD, 2015). Nevertheless, Norway is home to about 72,000 species, with 47,000 documented by Science (NOU 2024:2, 2024). This diversity is owed to Norway's varied geological and climatic features, encompassing 26 vegetation regions (NOU 2024:2, 2024). Norwegian habitats thus range from rivers, lakes, wetlands, open lowlands, mountains, polar regions, marine ecosystems, and forests (KMD, 2015). Forests, covering about a third of Norway, host the majority of its known species (NOU 2024:2, 2024).

Multiple factors contribute to biodiversity loss in Norway, including land use change, climate change, pollution, the introduction of alien species, and species harvesting (Artsdatabanken, 2021; NOU 2024:2, 2024). Land use change is recognised as a primary driver of biodiversity decline worldwide (Brondizio et al., 2019) and in Norway, affecting nine out of ten endangered species (Artsdatabanken, 2021).

To protect its biodiversity, Norway has set three national targets: 1) ensuring that ecosystems are in good condition to provide ecosystem services, 2) conserving endangered species and habitats, and 3) preserving selected natural areas for the benefit of future generations (KMD, 2015). The Norwegian government is currently developing a national action plan to meet the goals outlined in the Kunming-Montreal Global Biodiversity Framework. These goals are expected to align with the country's climate plan, scheduled for release later this year (KMD, 2023; NOU 2024:2, 2024). However, ongoing construction plans by Norwegian municipalities still primarily target forest areas as potential building sites. Natural open vegetation, wetlands, and other landscape types may also be destroyed for further infrastructural development. This includes constructing energy production facilities (Simensen et al., 2023).

1.4 The impacts of renewable electricity production on biodiversity

Hydropower

Building a hydropower plant requires space for the power station and its associated dams, tunnels, canals, and access roads (Gasparatos et al., 2017; Gracey & Verones, 2016). Hydropower plants are often built in remote areas, and their construction results in habitat loss (UNEP, 2016). Moreover, the construction of dams often leads to additional infrastructure development, such as new settlements (Zarfl et al., 2019).

Creating reservoirs contributes to terrestrial habitat loss as areas become inundated and create a barrier for species on land (Gracey & Verones, 2016). Reservoirs represent a homogenous body of water, offering a low-quality habitat for aquatic species (Sánchez-Zapata et al., 2016; UNEP, 2016). Furthermore, as reservoirs may inundate habitats previously covered with vegetation, they are responsible for the decomposition of plants, emitting greenhouse gas emissions such as methane and carbon dioxide (Gasparatos et al., 2017; Sánchez-Zapata et al., 2016; UNEP, 2016).

As dams are built on lakes and rivers, they hinder the natural movement of aquatic and terrestrial species and fragment rivers (Gasparatos et al., 2017; Geist, 2021; Sánchez-Zapata et al., 2016; UNEP, 2016; van Treeck et al., 2022). This particularly affects migratory fish, such as salmonids (Family Salmonidae) or clupeids (Family Clupeidae) (Sánchez-Zapata et al., 2016; van Treeck et al., 2022).

The construction of hydropower facilities also reduces the movement of sediments (Gasparatos et al., 2017; van Treeck et al., 2022), which are essential for nutrient exchange and the formation of floodplains (Gracey & Verones, 2016; UNEP, 2016). The turbines pose a threat to fish species, yet the level of risk depends on several factors, such as turbine type, operation, and the characteristics of the fish species (Geist, 2021; van Treeck et al., 2022). For example, species with elongated bodies are more prone to fatalities caused by turbines (Geist, 2021; Sánchez-Zapata et al., 2016).

Additionally, hydropower plants alter the natural water flow (Geist, 2021; Gracey & Verones, 2016; Sánchez-Zapata et al., 2016; UNEP, 2016; van Treeck et al., 2022). This adversely affects ecosystems such as floodplains, riparian areas, estuaries, and deltas (Kuriqi et al., 2021; Sánchez-Zapata et al., 2016; UNEP, 2016) and reduces species richness, including macroinvertebrates, fish, and riparian species (Gracey & Verones, 2016). Changes in water flow also impact the amount of water and its quality by altering temperature, nutrient exchange, organic material, turbidity, and oxygen levels (Gracey & Verones, 2016; Kuriqi et al., 2021). For instance, hydropower plants can release either epilimnetic (i.e., upper warmer water layer) or hypolimnetic (i.e., bottom cold-water layer) water from the reservoir into downstream rivers, thereby influencing river water temperature and affecting aquatic species (Gracey & Verones, 2016).

Onshore wind power

Wind farms are associated with direct and indirect habitat loss, as they occupy the landscape throughout their operational phase and require vegetation removal and soil grading (Gasparatos et al., 2017; Laranjeiro et al., 2018; Pereira et al., 2018; Sánchez-Zapata et al., 2016). Notably, the road network leading to the turbines contributes to the overall areal loss (Helldin et al., 2012). These roads also introduce additional disturbance effects by providing increased access to recreational areas, thereby increasing human presence and affecting species' activity and movement patterns. The increased human activity may explain why animals, particularly mammals, tend to avoid areas with wind farms (Helldin et al., 2012; Pereira et al., 2018).

Wind farms can also function as barriers, compelling birds to alter their flight paths to avoid turbines. This results in longer than usual distances travelled and potentially impacts their cumulative energy consumption (Laranjeiro et al., 2018; Pereira et al., 2018; Rydell et al., 2012).

A major concern related to wind farms is wildlife mortality, with hundreds to thousands of birds annually colliding with wind turbines (Gasparatos et al., 2017; Laranjeiro et al., 2018; Loss et al., 2013; Pereira et al., 2018; Rydell et al., 2012; Sánchez-Zapata et al., 2016). Importantly, a few turbines are responsible for most collisions, especially those near migration routes or mountain ridges (Laranjeiro et al., 2018; Pereira et al., 2018; Rydell et al., 2012; Sánchez-Zapata et al., 2016). Turbines operating at night or in adverse weather conditions may further contribute to species casualties (Sánchez-Zapata et al., 2016). Raptors, grouse, gulls, and terns are the bird species most affected by collisions (Rydell et al., 2012; Sánchez-Zapata et al., 2016).

Wind turbines also affect bat populations, potentially even more so than birds (Gasparatos et al., 2017; Sánchez-Zapata et al., 2016). Bats can collide with turbines or experience internal haemorrhaging due to reduced air pressure (Sánchez-Zapata et al., 2016). Aerial-hawking bats and species that are fast flyers and favour open habitats are particularly susceptible to turbine-related fatalities (Arnett et al., 2016).

1.5 The impacts of electricity transmission on biodiversity

Collision

Collisions occur when a bird collides with the wires of power lines during flight, potentially resulting in direct mortality or severe injuries (Bernardino et al., 2018; Bevanger, 1998; Richardson et al., 2017; Rioux et al., 2013). Collisions affect hundreds of millions of birds globally (Loss et al., 2014; Rioux et al., 2013), and it is one of the most studied impacts of the electric grid on biodiversity (Biasotto & Kindel, 2018; Richardson et al., 2017).

Several factors contribute to the susceptibility of species to power line collisions. Morphological features play an important role, with poor fliers having a higher chance of colliding since they cannot manoeuvre their flight well (Bernardino et al., 2018; Janss, 2000; Rubolini et al., 2005). Poor fliers can be categorised as birds with high wind loading (i.e., body weight relatively larger than wings) and a low wing aspect (i.e., broad wings) (Bernardino et al., 2018; Bevanger, 1998; Rayner, 1988). Additionally, the perception of power lines may affect collision risk, as some birds might not see the power lines in time (Martin, 2011; Martin & Shaw, 2010).

Behavioural traits also influence collision susceptibility. Birds that fly together in flocks (gregarious species) may have lower visibility to avoid power lines (Bernardino et al., 2018; Bevanger, 1998). Migratory birds, common collision victims, may fly at low altitudes under unfavourable weather conditions, be unfamiliar with the area, and tend to fly in groups (Bernardino et al., 2018; Bevanger, 1998). In addition, certain flight behaviours, such as hunting, displaying courtship or defending territories, can reduce attention to obstacles and increase the risk of collisions (Bernardino et al., 2018; Bevanger, 1998).

Species-specific factors may also contribute to collision susceptibility. For instance, age, as juveniles have less flying experience and have a higher risk of colliding with wires (Bernardino et al., 2018; Bevanger, 1998; Janss, 2000; Schaub & Pradel, 2004; Škorpíková et al., 2019).

Not only do species traits play a role in the chance of colliding, but also the technical aspects of the power lines. Thin-diameter or very tall wires increase the likelihood of collisions (Bernardino et al., 2018). This is especially true for the ground wire, the uppermost wire on transmission lines, designed to protect the phase conductors and pylons from lightning strikes (APLIC, 2012). In addition, reducing the number of vertical wire levels can decrease collision rates (APLIC, 2012; Bernardino et al., 2018; Gális et al., 2019). Generally, since transmission lines are taller, they have higher bird collision rates than distribution lines (Bernardino et al., 2018).

The location of power lines also influences the chance of collisions. Topography and habitat types attractive to birds can contribute to collision risk. This is also true for harsh weather conditions that affect flight behaviour, manoeuvrability, or vision (Bernardino et al., 2018).

Waterfowls and screamers (Order Anseriformes), waders, gulls and auks (Order Charadriiformes), storks (Order Ciconiiformes), rails, coots and cranes (Order Gruiformes) are common victims of collision (Bernardino et al., 2018; Bevanger, 1998; Gális et al., 2019; Jenkins et al., 2010; Rioux et al., 2013; Rubolini et al., 2005; Schaub & Pradel, 2004).

Electrocution

Electrocution is another well-documented impact of power lines on avian species (Biasotto & Kindel, 2018; Richardson et al., 2017). Electrocution occurs when a species simultaneously touches two conductors or a conductor and a grounded part, resulting in electrocution (APLIC, 2006; Bevanger, 1998; Eccleston & Harness, 2018; Loss et al., 2014). In the United States alone, approximately one million to 11.6 million birds die every year due to electrocution (Loss et al., 2014).

Larger birds face a higher risk of electrocution, given their increased likelihood of reaching both a conductor and a grounded component at the same time (Eccleston & Harness, 2018; Lehman et al., 2007). Dwyer et al. (2016) highlighted the relationship between avian electrocution risk with hazard and avian exposure. Hazard exposure refers to the configuration of the pylons, which is crucial to the electrocution risk (Eccleston & Harness, 2018; Gális et al., 2019; Lehman et al., 2007; Škorpíková et al., 2019). For instance, pylons with transformers significantly increase the risk of electrocution (Hernández-Lambraño et al., 2018; Kolnegari et al., 2021). Avian exposure involves bird behaviour and habitat features that attract species to perch on pylons (Dwyer et al., 2016). Predators often choose pylons for perching as they offer a good viewpoint for hunting (D'Amico et al., 2018), especially in open habitats lacking natural perch sites (Eccleston & Harness, 2018; Lehman et al., 2007; Tintó et al., 2010).

Like collisions, other factors contribute to a species' susceptibility to electrocution, including age, sex, prey availability, seasons, and weather conditions (Bevanger, 1998; Eccleston & Harness, 2018; Lehman et al., 2007).

Electrocution affects mostly birds of prey: diurnal raptors (Order Accipitriformes), falcons (Order Falconiformes), and owls (Order Strigiformes) (Bevanger, 1998; Gális et al., 2019; Janss, 2000; Lehman et al., 2007; Škorpíková et al., 2019). Yet storks and large passerines (Order Passeriformes), such as crows, ravens, and magpies, are also frequently found dead under pylons (Bevanger, 1998; Gális et al., 2019; Janss, 2000). In addition, bats are also electrocuted by power lines (Tella et al., 2020).

Habitat conversion, fragmentation, and loss

During construction, vegetation must be removed to establish the rights-of-way, the power line corridor. This clearance is essential for access and to minimise the risk of outages due to the grounding of wires by surrounding trees (NVE, 2016; Poulos & Camp, 2010). The width of the rights-of-way varies depending on its voltage (APLIC, 2012; NVE, 2016), potentially reaching 100 metres (Gardiner et al., 2018; Latham & Boutin, 2015). While power lines are concentrated in urban areas and often aligned with roads, their expansive network traverses natural landscapes, connecting electricity generation stations to consumers (Latham & Boutin, 2015). Consequently, building the rights-of-way may result in habitat fragmentation and a reduction in habitat size (Biasotto & Kindel, 2018; Richardson et al., 2017), as the removal of vegetation can affect a range of forest mammal species from rodents (Storm & Choate, 2012) to ungulates (Skarin & Åhman, 2014; Vistnes & Nellemann, 2001, 2008). Insects, amphibians, and reptiles might also reduce their habitat use in rights-of-way corridors (Richardson et al., 2017).

While power line construction leads to habitat conversion, it can benefit some species. Rights-of-way also serve as suitable open habitats for pollinators (Biasotto & Kindel, 2018; Steinert et al., 2021; Wagner et al., 2019) and offer foraging opportunities for ungulates (Bartzke et al., 2014; Biasotto & Kindel, 2018).

Other impacts

Numerous other impacts on biodiversity are associated with power lines. Removing vegetation during construction can facilitate the colonisation of invasive plant species in the rights-of-way (Biasotto & Kindel, 2018; Gardiner et al., 2018). While some studies suggest increased species richness within power lines' corridors, most fail to distinguish between native and invasive species (Biasotto & Kindel, 2018). Additionally, invasive species in rights-of-way may intensify fire risk (Biasotto & Kindel, 2018). Wildlife electrocutions can lead to short circuits, potentially starting a fire as the electrified animal ignites and falls to the ground, setting the vegetation on fire (Collins et al., 2016; Keeley & Syphard, 2018). While fire ignition due to electrocution is rare, the likelihood rises in areas with a seasonally dry climate (Eccleston et al., 2023).

Furthermore, linear corridors, such as power lines, are often selected as movement corridors by predators, influencing the dynamic between prey and predators, as observed in reindeer (DeMars & Boutin, 2018; Dickie et al., 2020, 2023). The construction of power lines disturbs reindeer herds, prompting them to avoid foraging habitats (Colman et al., 2015; Eftestøl et al., 2016). However, power lines do not seem to disturb reindeer during the operational phase (Reimers et al., 2020). Finally, several environmental studies have highlighted potential impacts such as noise, soil degradation, hydrological changes, and air pollution. However, these have not been thoroughly assessed (Biasotto & Kindel, 2018).

1.6 Life cycle assessment

The conflict between the inevitable necessity and promotion of renewable electricity production and the need to conserve biodiversity in Norway underscores the urgency to better understand the trade-offs between these two goals. A systematic quantification of the potential impacts of renewable electricity systems in a holistic approach is beneficial in evaluating these trade-offs more effectively.

Life cycle assessment (LCA) is a suitable instrument for analysing trade-offs between the environmental impacts of products throughout their various life cycle stages (Hellweg et al., 2023). LCA serves as a framework designed to incorporate all environmental impacts linked to a product or a service from raw materials extraction, production, and transport to the use phase, recycling and disposal (ISO, 2006). Each life cycle phase contributes a different set of impacts on the environment. Adopting a system-wide approach allows LCA to identify impact hotspots across life cycle stages (Bjørn et al., 2018; Hellweg et al., 2023). Furthermore, it facilitates the comparison of various impact pathways (e.g., climate change, human toxicity, and land use), thereby highlighting which impact pathways introduce higher environmental effects (Bjørn et al., 2018). This is important, as it reveals the trade-offs across environmental impacts: actions taken to reduce one impact may negatively affect a different impact (Bjørn et al., 2018). For instance, LCA can demonstrate how further construction of renewable energy positively influences the climate and human health yet, at the same time, results in greater damage to ecosystem quality (Hellweg et al., 2023). The LCA framework comprises four phases (Bjørn et al., 2018; ISO, 2006), as illustrated in Figure 1.4:

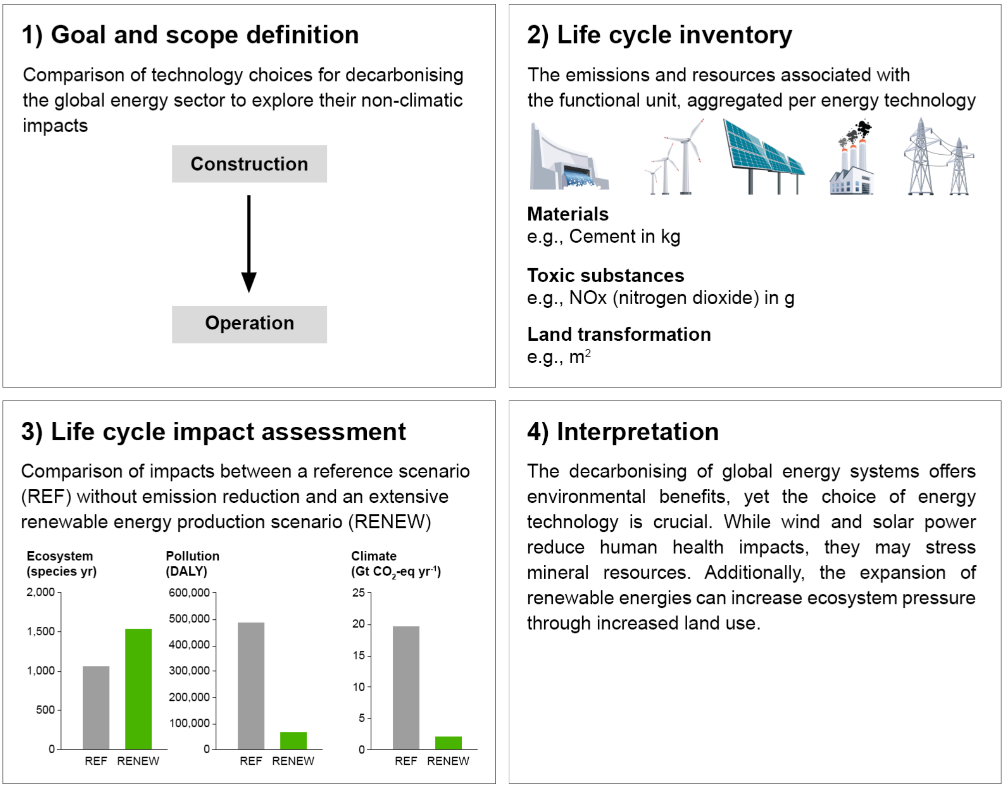

Figure 1.4. The four phases of LCA. Inspired by Figure 1 in Hellweg et al. (2023). Data based on Luderer et al. (2019). The graph describing the third phase originated from Figure 3 in Hellweg et al. (2023), modified. The icons were created by petovarga (2023).

1) *Goal and scope definition* is the initial phase where several essential parameters are defined. For instance, the functional unit (i.e., the quantitative representation of the assessed product or service, e.g., one kilowatt-hour of electricity produced or transmitted), which activities, processes, and impacts are to be evaluated, and the spatial and temporal settings of the analysis.

2) *Life cycle inventory* (LCI) is the data collection of all associated elementary physical flows of relevant inputs and outputs crucial for the functional unit. Inputs could be resources and materials required to produce and transmit electricity, while outputs could be emissions and areas transformed and occupied for electricity generation and transmission infrastructure.

3) *Life cycle impact assessment* (LCIA) is the translation of the life cycle inventory into environmental impacts. This involves selecting impact categories (e.g., land occupation, climate change, and human toxicity), classifying the elementary flows into these impact categories, and quantifying their total impact by applying the so-called characterisation factors. These impact categories are aggregated into areas of protection, i.e., ecosystem quality, human health, and natural resources.

4) *Interpretation* is the final stage that explains the results of stages two and three (LCI and LCIA) within the framework defined in stage one. Sensitivity and uncertainty analyses are relevant in this stage, as they can enhance the robustness of the analysis outcomes.

Area of protection: ecosystem quality

Aggregating impact categories under areas of protection aims to simplify results for policy-makers and enhance communication by avoiding an overwhelming list of impact indicators (Verones et al., 2017). Although LCA encompasses multiple areas of protection, this thesis concentrates on one area - ecosystem quality. This area includes various impact pathways such as eutrophication, ecotoxicity, acidification, land occupation and transformation (Verones et al., 2017, 2020). The recommended metric for evaluating damage to ecosystem quality is the potentially disappeared fraction of species, abbreviated as PDF, which illustrates the relative loss of species richness due to a certain stressor (Verones et al., 2017; Woods et al., 2018). Despite its limitations, as species richness alone cannot indicate the state of biodiversity (Damiani et al., 2023; Duelli & Obrist, 2003; Winter et al., 2017; Woods et al., 2018), the PDF stands out as the best currently available indicator for assessing biodiversity loss (Verones et al., 2017). The PDF can quantify regional and global impacts on biodiversity across different taxonomic groups (Dorber et al., 2020b; Scherer et al., 2023).

LCA and energy systems

There has been a significant increase in scientific papers addressing LCA and energy systems over the recent decades (Barros et al., 2020; Laurent et al., 2018). This yielded extensive datasets linking the energy sector to LCA, which allows the comparison of different energy technologies (Hellweg et al., 2023). LCA studies show that fossil fuels exhibit higher environmental impacts than low-carbon technologies (Gibon et al., 2017; Hellweg et al., 2023; Laurent et al., 2018). Moreover, the LCA framework can be used to model future scenarios exploring potential environmental impacts by phasing out fossil fuels and promoting renewable energy production (Hellweg et al., 2023; Hertwich et al., 2015; Luderer et al., 2019; Pehl et al., 2017). The recent development of regionalised impact assessment models provides more realistic results, presenting a geographic-specific assessment rather than a generic one (Verones et al., 2020). Regionalised models can be used to show how impacts vary spatially. For instance, they can identify which wind power plants have higher impacts on bird richness (May et al., 2021) or determine how to minimise the biodiversity impacts of future reservoirs (Dorber et al., 2020a).

Therefore, LCA can serve as a valuable instrument to support policy-makers in designing a sustainable, environmentally friendly energy transition (Hellweg et al., 2023; Luderer et al., 2019). Its widespread use is evident, as the European Union (EU) recognised LCA as the best available tool to assess environmental impacts associated with products (EU Commission, 2003) and integrated it gradually into its environmental policies (Sala et al., 2021). Similarly, the Norwegian government acknowledges the value of LCA in diverse sectors, e.g., seafood products, transport, and construction (KMD, 2002, 2006, 2007; SD, 2013).

1.7 Research gap

Although the environmental impacts of renewables have been extensively studied in the LCA literature (Asdrubali et al., 2015), these studies primarily focus on climate change (Barros et al., 2020), often overlooking impacts associated with biodiversity loss. Additionally, most of the assessments modelled the impacts at the midpoint level (Barros et al., 2020).

A midpoint indicator represents impacts situated along the impact pathway. This approach offers impact scores for comparison within each impact category (Hellweg et al., 2023; Rosenbaum et al., 2018b). Midpoint indicators are favoured as they are often easier to model (Barros et al., 2020) and have strong scientific robustness (Hauschild & Huijbregts, 2015; Rosenbaum et al., 2018a). Conversely, endpoint indicators represent damage to areas of protection (i.e., ecosystem quality). These indicators characterise impacts at the end of the impact pathway and allow for comparisons across impact categories within a specific area of protection (Hellweg et al., 2023; Rosenbaum et al., 2018b). Although endpoint indicators are often linked with higher uncertainty due to their complex models and the incorporation of extensive datasets, they offer a greater environmental relevance when compared to midpoint indicators (Rosenbaum et al., 2018a).

For example, when assessing climate change impacts, the CO_2-equivalents (i.e., unit for emitted greenhouse gas emission) act as a midpoint unit, while the PDF (i.e., the potentially disappeared fraction of species) serves as an endpoint unit for ecosystem quality, representing the fraction of species that will disappear due to that impact (Rosenbaum et al., 2018b; Woods et al., 2018).

Research on renewable energy within LCA that accounts for the ecosystem quality area of protection covers limited impact pathways at a midpoint level, such as eutrophication, ecotoxicity, acidification, land occupation and transformation (Gibon et al., 2017; Hertwich et al., 2015; Luderer et al., 2019). Nevertheless, recent developments in LCIA have begun addressing this gap by introducing new endpoint indicators. LCIA models quantified, for example, the effects of barrier, collision, disturbance, and habitat loss impacts of wind turbines on global and Norwegian bird richness (May et al., 2020, 2021). Additionally, models were developed to assess the impacts of land inundation on terrestrial species and water consumption on aquatic biodiversity caused by the construction of hydropower reservoirs (Dorber et al., 2019; 2020b). Dorber et al. (2018, 2019) have contributed LCI data on reservoir land occupation for Norway and the net water consumption values for Norwegian hydropower reservoirs.

The quantification of the biodiversity impacts linked to power lines remained unaddressed, as LCA studies tend to concentrate solely on energy production technologies and neglect power lines altogether. This gap also persists in the recently developed LCIA biodiversity models, as their scope covered only impacts related to renewable electricity production from hydropower or wind power plants. Gargiulo et al. (2017) compiled numerous LCA studies on power lines, showing that they cover many impact pathways. Among them, climate change, freshwater eutrophication, and resource depletion were always assessed. Notably, none of the studies evaluated the potential impacts of collision, electrocution, or habitat fragmentation (Gargiulo et al., 2017) due to the absence of a methodology for quantifying these impacts.

Only a few LCA energy studies have incorporated power lines in their analyses but at the midpoint level. For example, Luderer et al. (2019) included the expansion of the transmission network in their energy transition scenarios. However, their assessment primarily focused on the impacts of land occupation and mineral resource depletion. Furthermore, their grid evaluation relied on energy system models incorporating variables of energy demand and renewables (Scholz et al., 2017; Ueckerdt et al., 2017) rather than geodata representing the locations where power lines would be constructed. Despite these limitations, Luderer et al. (2019) demonstrated a significant impact of grid expansion on ecosystem quality due to land occupation. This finding aligns with forecasts indicating that the global grid network will double its current length of 100 million kilometres by 2025 (DNV, 2023).

There is a pressing need for the rapid development of the grid globally (DNV, 2023; IEA, 2023) and in Norway (NOU 2022:6, 2022; Statnett, 2023c, 2023a). While LCA is a proven tool to support the transition to low-carbon technologies, the framework requires additional regionalised LCIA models to cover the wide range of biodiversity impacts (Hellweg et al., 2023; Luderer et al., 2019). Therefore, developing biodiversity LCIA models to assess the impacts of power lines on species richness is crucial. Such models can facilitate a holistic assessment of electricity production and transmission, offering a better understanding of the impacts of the renewable electricity system on ecosystem quality.

Another essential step is to adopt a system-wide perspective by incorporating the existing biodiversity LCIA models related to renewables, encompassing the biodiversity impacts of hydropower plants, wind power, and power lines. This approach can provide an overview of the overall current biodiversity impacts arising from the renewable electricity system in Norway and serve as a baseline for future scenario analyses. Given the inevitable expansion of renewables in the country, such analyses can become instrumental in assessing the promotion of renewable electricity production while offering strategies for mitigating its impacts on biodiversity. Notably, LCIA models have already demonstrated their capability to map biodiversity impacts spatially, pinpointing areas with higher effects on species richness (Chaudhary et al., 2015; Dorber et al., 2020a; Pierrat et al., 2023; Scherer et al., 2023).

This thesis focuses on regional models to assess the effects of the Norwegian electricity system on biodiversity. This is important, as regional models can provide more accurate assessments (Mutel et al., 2019) by applying specific data, i.e., locations of power plants, power lines, and high-resolution species richness maps. However, such analyses cannot be compared with other regions (Verones et al., 2022). Furthermore, Norway's reliance on neighbouring countries for electricity exchange, both in exports and imports (NVE, 2022, 2023b; Statnett, 2023b), underscores the complementary nature of electricity systems. A broader international perspective can illuminate relationships between countries regarding electricity sharing, contributing to a more robust global energy transition. Therefore, regional LCIA models must be easily transferable to other regions, facilitating globally comparable models. This is particularly critical in the context of biodiversity, where certain regions may experience higher impacts due to species richness or a significant share of endemic species, i.e., species confined to specific areas and found nowhere else (Verones et al., 2022).

1.8 Research aim

This thesis aims to develop LCIA models that address impact pathways associated with power lines and integrate them with existing LCIA biodiversity models for renewable electricity production. This results in a holistic, system-wide analysis of the Norwegian renewable electricity system's impacts on species richness. Although the LCIA models are primarily designed for Norway, they are adaptable to other regions, given that suitable input data are available to allow global applicability and coverage.

The research goals of the thesis are:

1. Develop spatially explicit LCIA models to quantify the main biodiversity impacts of power lines: collision, electrocution, habitat loss, and habitat conversion and fragmentation (Chapters 2, 3, and 4).

2. Demonstrate how LCIA biodiversity models for power lines can be transferable to other regions (Chapter 4).
3. Integrate the developed biodiversity LCIA models of power lines with existing models that quantify the impacts of renewable electricity production (i.e., hydropower and wind power) on species richness in Norway. The integration of these models aims to present the current overall biodiversity impacts of the Norwegian renewable electricity system (Chapter 5).
4. Discuss the suggested methodology's relevance and applicability within the LCA framework. Analyse its limitations and suggest recommendations for potential future research gaps (Chapter 6).

The research goals unfold across five chapters. Chapter 2 introduces the methodology for two LCIA models, quantifying the impacts of collision and electrocution on bird richness in Norway. Chapter 3 presents an adaptation of an existing LCIA model for habitat conversion and fragmentation to power lines in Norway. The adapted model is integrated with the collision and electrocution models to comprehensively assess the primary effects of power lines on Norwegian bird and mammal diversity. Chapter 4 introduces an adaptation of a habitat loss LCIA model to power lines. The model assesses regional and global habitat loss impacts of power lines, applied to 138 countries. In Chapter 5, electricity production and transmission models are combined to quantify the overall biodiversity impacts of the renewable electricity system in Norway. Chapter 6 discusses the contribution and usability of the developed models, and their limitations and uncertainties are addressed.

References

APLIC. (2006). *Suggested Practices for Avian Protection on Power Lines: The State of the Art in 2006*. Edison Electric Institute and Avian Power Line Interaction Committee (APLIC), and the California Energy Commission. Washington, D.C and Sacramento, CA.

APLIC. (2012). *Reducing Avian Collisions with Power Lines: The State of the Art in 2012*. Edison Electric Institute and Avian Power Line Interaction Committee (APLIC). Washington, D.C.

Arnett, E. B., Baerwald, E. F., Mathews, F., Rodrigues, L., Rodríguez-Durán, A., Rydell, J., Villegas-Patraca, R., & Voigt, C. C. (2016). Impacts of Wind Energy Development on Bats: A Global Perspective. In C. C. Voigt & T. Kingston (Eds.), *Bats in the Anthropocene: Conservation of Bats in a Changing World* (pp. 295–323). Springer International Publishing. https://doi.org/10.1007/978-3-319-25220-9_11

Artsdatabanken. (2021). *Påvirkningsfaktorer. Norsk rødliste for arter 2021*. https://artsdatabanken.no/rodlisteforarter2021/Resultater/Pavirkningsfaktorer, accessed 10.12.23.

Asdrubali, F., Baldinelli, G., D'Alessandro, F., & Scrucca, F. (2015). Life cycle assessment of electricity production from renewable energies: Review and results harmonization.*Renewable and Sustainable Energy Reviews*, *42*, 1113–1122. https://doi.org/10.1016/j.rser.2014.10.082

Barros, M. V., Salvador, R., Piekarski, C. M., de Francisco, A. C., & Freire, F. M. C. S. (2020). Life cycle assessment of electricity generation: A review of the characteristics of existing literature. *The International Journal of Life Cycle Assessment*, *25*(1), 36–54. https://doi.org/10.1007/s11367-019-01652-4

Bartzke, G. S., May, R., Bevanger, K., Stokke, S., & Roskaft, E. (2014). The effects of power lines on ungulates and implications for power line routing and rights-of-way management. *International Journal of Biodiversity and Conservation*, *6*(9), 647–662. https://doi.org/10.5897/IJBC2014.0716

Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J. F., Marques, A. T., Martins, R. C., Shaw, J. M., Silva, J. P., & Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation*, *222*, 1–13. https://doi.org/10.1016/j.biocon.2018.02.029

Bevanger, K. (1998). Biological and conservation aspects of bird mortality caused by electricity power lines: A review. *Biological Conservation*, *86*(1), 67–76. https://doi.org/10.1016/S0006-3207(97)00176-6

Biasotto, L. D., & Kindel, A. (2018). Power lines and impacts on biodiversity: A systematic review. *Environmental Impact Assessment Review*, *71*, 110–119. https://doi.org/10.1016/j.eiar.2018.04.010

Bjørn, A., Owsianiak, M., Molin, C., & Laurent, A. (2018). Main Characteristics of LCA. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 9–16). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_2

Brondizio, E. S., Settele, J., Diaz, S., & Ngo, H. T. (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Bryant, M. (2023). Storm Hans causes havoc in Norway with heaviest rain in 25 years forecast. *The Guardian*. https://www.theguardian.com/world/2023/aug/08/storm-hans-causes-havoc-in-norway-with-heaviest-rain-in-25-years-forecast, accessed 23.01.24.

Bryant, M. (2024). Oslo airport grounds flights amid heavy snowfall. *The Guardian*. https://www.theguardian.com/weather/2024/jan/17/oslo-airport-grounds-flights-amid-heavy-snowfall, accessed 23.01.24.

Chaudhary, A., Verones, F., de Baan, L., & Hellweg, S. (2015). Quantifying Land Use Impacts on Biodiversity: Combining Species–Area Models and Vulnerability Indicators. *Environmental Science & Technology*, *49*(16), 9987–9995. https://doi.org/10.1021/acs.est.5b02507

Collins, K. M., Penman, T. D., & Price, O. F. (2016). Some Wildfire Ignition Causes Pose More Risk of Destroying Houses than Others. *PLOS ONE*, *11*(9), e0162083. https://doi.org/10.1371/journal.pone.0162083

Colman, J. E., Tsegaye, D., Flydal, K., Rivrud, I. M., Reimers, E., & Eftestøl, S. (2015). High-voltage power lines near wild reindeer calving areas. *European Journal of Wildlife Research*, *61*(6), 881–893. https://doi.org/10.1007/s10344-015-0965-x

COP28. (2023). *COP28 delivers historic consensus in Dubai to accelerate climate action*. https://www.cop28.com/en/news/2023/12/COP28-delivers-historic-consensus-in-Dubai-to-accelerate-climate-action, accessed 29.12.23.

Copernicus. (2023a). *2023: A year of intense global wildfire activity*. https://atmosphere.copernicus.eu/2023-year-intense-global-wildfire-activity, accessed 28.12.23.

Copernicus. (2023b). *European summer 2023: A season of contrasting extremes*. https://climate.copernicus.eu/european-summer-2023-season-contrasting-extremes, accessed 28.12.23.

Copernicus. (2023c). *Record warm November consolidates 2023 as the warmest year*. https://climate.copernicus.eu/record-warm-november-consolidates-2023-warmest-year, accessed 28.12.23.

Copernicus. (2024). *Warmest December concludes warmest year on record*. https://climate.copernicus.eu/warmest-december-concludes-warmest-year-record, accessed 19.01.24.

Damiani, M., Sinkko, T., Caldeira, C., Tosches, D., Robuchon, M., & Sala, S. (2023). Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. *Environmental Impact Assessment Review*, *101*, 107134. https://doi.org/10.1016/j.eiar.2023.107134

D'Amico, M., Catry, I., Martins, R. C., Ascensão, F., Barrientos, R., & Moreira, F. (2018). Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines. *Ambio*, *47*(6), 650–656. https://doi.org/10.1007/s13280-018-1025-z

DeMars, C. A., & Boutin, S. (2018). Nowhere to hide: Effects of linear features on predator–prey dynamics in a large mammal system. *Journal of Animal Ecology*, *87*(1), 274–284. https://doi.org/10.1111/1365-2656.12760

Dickie, M., McNay, S. R., Sutherland, G. D., Cody, M., & Avgar, T. (2020). Corridors or risk? Movement along, and use of, linear features varies predictably among large mammal predator and prey species. *Journal of Animal Ecology*, *89*(2), 623–634. https://doi.org/10.1111/1365-2656.13130

Dickie, M., Sherman, G. G., Sutherland, G. D., McNay, R. S., & Cody, M. (2023). Evaluating the impact of caribou habitat restoration on predator and prey movement. *Conservation Biology*, *37*(2), e14004. https://doi.org/10.1111/cobi.14004

DNV. (2023). *Energy Transition Outlook 2023—A global and regional forecast to 2050*. https://www.dnv.com/energy-transition-outlook/

Dorber, M., Arvesen, A., Gernaat, D., & Verones, F. (2020a). Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection. *Scientific Reports*, *10*(1), Article 1. https://doi.org/10.1038/s41598-020-78444-6

Dorber, M., Kuipers, K., & Verones, F. (2020b). Global characterization factors for terrestrial biodiversity impacts of future land inundation in Life Cycle Assessment. *Science of The Total Environment*, *712*, 134582. https://doi.org/10.1016/j.scitotenv.2019.134582

Dorber, M., Mattson, K. R., Sandlund, O. T., May, R., & Verones, F. (2019). Quantifying net water consumption of Norwegian hydropower reservoirs and related aquatic biodiversity impacts in Life Cycle Assessment. *Environmental Impact Assessment Review*, *76*, 36–46. https://doi.org/10.1016/j.eiar.2018.12.002

Dorber, M., May, R., & Verones, F. (2018). Modeling Net Land Occupation of Hydropower Reservoirs in Norway for Use in Life Cycle Assessment. *Environmental Science & Technology*, *52*(4), 2375–2384. https://doi.org/10.1021/acs.est.7b05125

Duelli, P., & Obrist, M. K. (2003). Biodiversity indicators: The choice of values and measures. *Agriculture, Ecosystems & Environment*, *98*(1), 87–98. https://doi.org/10.1016/S0167-8809(03)00072-0

Dwyer, J. F., Harness, R. E., Gerber, B. D., Landon, M. A., Petersen, P., Austin, D. D., Woodbridge, B., Williams, G. E., & Eccleston, D. (2016). Power pole density informs spatial prioritization for mitigating avian electrocution. *The Journal of Wildlife Management*, *80*(4), 634–642. https://doi.org/10.1002/jwmg.1048

Eccleston, D., Groh, N., Harness, R., Petersen, P., Brockbank, R., & Rogers, T. (2023). *Ignition Prevention on Overhead Powerlines: Assessing and Mitigating Risk from Wildlife.* In: L. Denney & N. Geagea Pupa (Eds.), *Environmental Concerns in Rights-of- Way Management 13th International Symposium* (pp. 383–391). Pique Publishing, Inc.

Eccleston, D. T., & Harness, R. E. (2018). Raptor Electrocutions and Power Line Collisions. In J. H. Sarasola, J. M. Grande, & J. J. Negro (Eds.), *Birds of Prey: Biology and conservation in the XXI century* (pp. 273–302). Springer International Publishing. https://doi.org/10.1007/978-3-319-73745-4_12

Eftestøl, S., Tsegaye, D., Flydal, K., & Colman, J. E. (2016). From high voltage (300 kV) to higher voltage (420 kV) power lines: Reindeer avoid construction activities. *Polar Biology*, *39*(4), 689–699. https://doi.org/10.1007/s00300-015-1825-6

ENTSO-E. (2023). *ENTSO-E Transparency Platform*. https://transparency.entsoe.eu/, accessed 07.12.23.

EU Commission. (2003). *Integrated Product Policy—Building on Environmental Life-Cycle Thinking* (302).

Gális, M., Naďo, L., Hapl, E., Šmídt, J., Deutschová, L., & Chavko, J. (2019). Comprehensive analysis of bird mortality along power distribution lines in Slovakia. *Raptor Journal*, *13*(1), 1–25. https://doi.org/10.2478/srj-2019-0006

Gardiner, M. M., Riley, C. B., Bommarco, R., & Öckinger, E. (2018). Rights-of-way: A potential conservation resource. *Frontiers in Ecology and the Environment*, *16*(3), 149–158. https://doi.org/10.1002/fee.1778

Gargiulo, A., Girardi, P., & Temporelli, A. (2017). LCA of electricity networks: A review. *The International Journal of Life Cycle Assessment*, *22*(10), 1502–1513. https://doi.org/10.1007/s11367-017-1279-x

Gasparatos, A., Doll, C. N. H., Esteban, M., Ahmed, A., & Olang, T. A. (2017). Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renewable and Sustainable Energy Reviews*, *70*, 161–184. https://doi.org/10.1016/j.rser.2016.08.030

Geist, J. (2021). Editorial: Green or red: Challenges for fish and freshwater biodiversity conservation related to hydropower. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *31*(7), 1551–1558. https://doi.org/10.1002/aqc.3597

Gibon, T., Arvesen, A., & Hertwich, E. G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews*, *76*, 1283–1290. https://doi.org/10.1016/j.rser.2017.03.078

Gracey, E. O., & Verones, F. (2016). Impacts from hydropower production on biodiversity in an LCA framework—Review and recommendations. *The International Journal of Life Cycle Assessment*, *21*(3), 412–428. https://doi.org/10.1007/s11367-016-1039-3

Hauschild, M. Z., & Huijbregts, M. A. J. (2015). Introducing Life Cycle Impact Assessment. In M. Z. Hauschild & M. A. J. Huijbregts (Eds.), *Life Cycle Impact Assessment* (pp. 1–16). Springer Netherlands. https://doi.org/10.1007/978-94-017-9744-3_1

Helldin, J. O., Jung, J., Neumann, W., & Olsson, M. (2012). *The impacts of wind power on terrestrial mammals: A synthesis*. Naturvårdsverket.

Hellweg, S., Benetto, E., Huijbregts, M. A. J., Verones, F., & Wood, R. (2023). Life-cycle assessment to guide solutions for the triple planetary crisis. *Nature Reviews Earth & Environment*, *4*(7), Article 7. https://doi.org/10.1038/s43017-023-00449-2

Hernández-Lambraño, R. E., Sánchez-Agudo, J. Á., & Carbonell, R. (2018). Where to start? Development of a spatial tool to prioritise retrofitting of power line poles that are dangerous to raptors. *Journal of Applied Ecology*, *55*(6), 2685–2697. https://doi.org/10.1111/1365-2664.13200

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., & Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies.

Proceedings of the National Academy of Sciences, *112*(20), 6277–6282. https://doi.org/10.1073/pnas.1312753111

IEA. (2023). *World Energy Outlook 2023*. International Energy Agency (IEA). Paris, France. https://origin.iea.org/reports/world-energy-outlook-2023

IEA. (2024). *Renewables 2023. Analysis and forecast to 2028*. International Energy Agency (IEA). Paris, France. https://prod.iea.org/reports/renewables-2023

IPCC. (2023). Summary for Policymakers. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–34). Intergovernmental Panel on Climate Change (IPCC). 10.59327/IPCC/AR6-9789291691647.001

ISO. (2006). *ISO 14044: Environmental Management—Life Cycle Assessment—Principles and Framework*. International Organization for Standardization (ISO). Geneva, Switzerland.

Janss, G. F. E. (2000). Avian mortality from power lines: A morphologic approach of a species-specific mortality. *Biological Conservation*, *95*(3), 353–359. https://doi.org/10.1016/S0006-3207(00)00021-5

Jenkins, A. R., Smallie, J. J., & Diamond, M. (2010). Avian collisions with power lines: A global review of causes and mitigation with a South African perspective. *Bird Conservation International*, *20*(3), 263–278. https://doi.org/10.1017/S0959270910000122

Keeley, J. E., & Syphard, A. D. (2018). Historical patterns of wildfire ignition sources in California ecosystems. *International Journal of Wildland Fire*, *27*(12), 781–799. https://doi.org/10.1071/WF18026

KMD. (2002). *St.meld. Nr. 12 (2001-2002)—Rent og rikt hav*. Klima- og miljødepartementet (KMD). https://www.regjeringen.no/no/dokumenter/stmeld-nr-12-2001-2002-/id195387/

KMD. (2006). *St.meld. Nr. 14 (2006-2007)—Sammen for et giftfritt miljø – forutsetninger for en tryggere fremtid*. Klima- og miljødepartementet (KMD). https://www.regjeringen.no/no/dokumenter/Stmeld-nr-14-2006-2007-/id441267/

KMD. (2007). *St.meld. Nr. 34 (2006-2007)—Norsk klimapolitikk*. Klima- og miljødepartementet (KMD). https://www.regjeringen.no/no/dokumenter/Stmeld-nr-34-2006-2007-/id473411/

KMD. (2015). *Meld. St. 14 (2015–2016)—Natur for livet—Norsk handlingsplan for naturmangfold*. Klima- og miljødepartementet (KMD). https://www.regjeringen.no/no/dokumenter/meld.-st.-14-20152016/id2468099/

KMD. (2021). *Meld. St. 13 (2020–2021)—Klimaplan for 2021–2030*. Klima- og miljødepartementet (KMD). https://www.regjeringen.no/no/dokumenter/meld.-st.-13-20202021/id2827405/

KMD. (2023). *Meld. St. 26 (2022–2023)—Klima i endring – sammen for et klimarobust samfunn*. Klima- og miljødepartementet (KMD). https://www.regjeringen.no/no/dokumenter/meld.-st.-26-20222023/id2985027/

Kolnegari, M., Conway, G. J., Basiri, A. A., Panter, C. T., Hazrati, M., Rafiee, M. S., Ferrer, M., & Dwyer, J. F. (2021). Electrical Components Involved in Avian-Caused Outages in Iran. *Bird Conservation International*, *31*(3), 364–378. https://doi.org/10.1017/S0959270920000507

Kuriqi, A., Pinheiro, A. N., Sordo-Ward, A., Bejarano, M. D., & Garrote, L. (2021). Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition. *Renewable and Sustainable Energy Reviews*, *142*, 110833. https://doi.org/10.1016/j.rser.2021.110833

Laranjeiro, T., May, R., & Verones, F. (2018). Impacts of onshore wind energy production on birds and bats: Recommendations for future life cycle impact assessment developments. *The International Journal of Life Cycle Assessment*, *23*(10), 2007–2023. https://doi.org/10.1007/s11367-017-1434-4

Latham, A. D. M., & Boutin, S. (2015). Impacts of Utility and Other Industrial Linear Corridors on Wildlife. In *Handbook of Road Ecology* (pp. 228–236). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118568170.ch27

Laurent, A., Espinosa, N., & Hauschild, M. Z. (2018). LCA of Energy Systems. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 633–668). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_26

Lehman, R. N., Kennedy, P. L., & Savidge, J. A. (2007). The state of the art in raptor electrocution research: A global review. *Biological Conservation*, *136*(2), 159–174. https://doi.org/10.1016/j.biocon.2006.09.015

Loss, S. R., Will, T., & Marra, P. P. (2013). Estimates of bird collision mortality at wind facilitiesin the contiguous United States. *Biological Conservation*, *168*, 201–209. https://doi.org/10.1016/j.biocon.2013.10.007

Loss, S. R., Will, T., & Marra, P. P. (2014). Refining Estimates of Bird Collision and Electrocution Mortality at Power Lines in the United States. *PLOS ONE*, *9*(7), e101565. https://doi.org/10.1371/journal.pone.0101565

Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., Fricko, O., Hejazi, M., Humpenöder, F., Iyer, G., Mima, S., Mouratiadou, I., Pietzcker, R. C., Popp, A., van den Berg, M., van Vuuren, D., & Hertwich, E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, *10*(1), Article 1. https://doi.org/10.1038/s41467-019-13067-8

Martin, G. R. (2011). Understanding bird collisions with man-made objects: A sensory ecology approach. *Ibis*, *153*(2), 239–254. https://doi.org/10.1111/j.1474-919X.2011.01117.x

Martin, G. R., & Shaw, J. M. (2010). Bird collisions with power lines: Failing to see the way ahead? *Biological Conservation*, *143*(11), 2695–2702. https://doi.org/10.1016/j.biocon.2010.07.014

May, R., Jackson, C. R., Middel, H., Stokke, B. G., & Verones, F. (2021). Life-cycle impacts of wind energy development on bird diversity in Norway. *Environmental Impact Assessment Review*, *90*, 106635. https://doi.org/10.1016/j.eiar.2021.106635

May, R., Middel, H., Stokke, B. G., Jackson, C., & Verones, F. (2020). Global life-cycle impacts of onshore wind-power plants on bird richness. *Environmental and Sustainability Indicators*, *8*, 100080. https://doi.org/10.1016/j.indic.2020.100080

MET. (2022). *Hetebølger i Norge 1961-2020* (1/2022). Meteorologisk institutt (MET).

Mutel, C., Liao, X., Patouillard, L., Bare, J., Fantke, P., Frischknecht, R., Hauschild, M., Jolliet, O., de Souza, D.M., Laurent, A., Pfister, S. & Verones, F. (2019). Overview and recommendations for regionalized life cycle impact assessment. *Int J Life Cycle Assess, 24*, 856–865. https://doi.org/10.1007/s11367-018-1539-4

NASA. (2023). *NASA Announces Summer 2023 Hottest on Record.* Climate Change: Vital Signs of the Planet. National Aeronautics and Space Administration (NASA). https://climate.nasa.gov/news/3282/nasa-announces-summer-2023-hottest-on-record, accessed 28.12.23.

NKSS. (2015). *Klima i Norge 2100: Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015* (2/2015). Norsk klimaservicesenter (NKSS).

NOU 2022:6. (2022). *Nett i tide—Om utvikling av strømnettet*. Noregs offentlege utgreiingar (NOU). https://www.regjeringen.no/no/dokumenter/nou-2022-6/id2918464/

NOU 2023:3. (2023). *Mer av alt – raskere, Energikommisjonens rapport.* Noregs offentlege utgreiingar (NOU). https://www.regjeringen.no/no/dokumenter/nou-2023-3/id2961311/

NOU 2023:25. (2023). *Omstilling til lavutslipp—Veivalg for klimapolitikken mot 2050* (2023:25). Noregs offentlege utgreiingar (NOU). https://www.regjeringen.no/no/dokumenter/nou-2023-25/id3006059/

NOU 2024:2. (2024). *I samspill med naturen—Naturrisiko for næringer, sektorer og samfunn i Norge*. Noregs offentlege utgreiingar (NOU). https://www.regjeringen.no/no/dokumenter/nou-2024-2/id3024887/

NVE. (2016). *Skogrydding i kraftledningstraséer—Forsyningssikkerhet, miljø- og landskapshensyn* (2–2016). Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/tilsyn/nytt-fra-miljoetilsynet/ny-veileder-om-skogrydding-i-kraftledningstraseer/

NVE. (2020a). *Det svinger mer med fornybar strøm: Sammenhengende vær i Nord-Europa skaper utfordringer i et fornybart kraftsystem* (44/2020). Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/nytt-fra-nve/nyheter-energi/sammenhengende-vaer-i-nord-europa-skaper-utfordringer-i-et-fornybart-kraftsystem/

NVE. (2020b). *Kraft fra land til norsk sokkel—Rapport 2020*. Noregs vassdrags- og energidirektorat (NVE).

NVE. (2022). *Norsk og nordisk effektbalanse fram mot 2030* (20/2022). Noregs vassdrags- og energidirektorat (NVE).

NVE. (2023a). *Data for utbygde vindkraftverk i Norge*. Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/energisystem/vindkraft/data-for-utbygde-vindkraftverk-i-norge/, accessed 07.12.23.

NVE. (2023b). *Langsiktig kraftmarkedsanalyse 2023: Energiomstillingen—En balansegang* (25/2023). Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/analyser-og-statistikk/langsiktig-kraftmarkedsanalyse/langsiktig-kraftmarkedsanalyse-2023/

NVE. (2023c). *Om magasinstatistikken*. Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/analyser-og-statistikk/om-magasinstatistikken/, accessed 10.01.24.

NVE. (2023d). *Oppdatert tall for magasinkapasitet i Norge*. Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/nytt-fra-nve/nyheter-energi/oppdatert-tall-for-magasinkapasitet-i-norge/, accessed 24.01.24.

NVE. (2023e). *Samlet energibruk—Energibruk etter vare: Samlet energibruk i Norge fordelt på forskjellige energivarer*. Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/energisystem/energibruk/samlet-energibruk/, accessed 09.12.23.

NVE. (2023f). *Solkraft*. Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/energisystem/solkraft/, accessed 26.01.24.

NVE. (2023g). *Vannkraft*. Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/energisystem/vannkraft/, accessed 24.01.24.

OED. (2020). *Meld. St. 28 (2019 – 2020)—Vindkraft på land—Endringer i konsesjonsbehandlingen*. Olje- og energidepartementet (OED). https://www.regjeringen.no/no/dokumenter/meld.-st.-28-20192020/id2714775/

OED. (2021). *Meld. St. 36 (2020–2021)—Energi til arbeid – langsiktig verdiskaping fra norske energiressurser*. Olje- og energidepartementet (OED). https://www.regjeringen.no/no/dokumenter/meld.-st.-36-20202021/id2860081/

OED. (2022). *Kraftproduksjon fordelt på prisområde*. Energifakta Norge. Olje- og energidepartementet (OED). https://energifaktanorge.no/norsk-energiforsyning/kraftmarkedet/kraftproduksjon-fordelt-pa-prisomrade/, accessed 26.01.24.

OED. (2023). *Regjeringens handlingsplan for raskere nettutbygging og bedre utnyttelse av nettet*. Olje- og energidepartementet (OED). https://www.regjeringen.no/globalassets/departementene/oed/ingrid/regjeringens-handlingsplan-for-raskere-nettutbygging-og-bedre-utnyttelse-av-nettet.pdf

Pereira, P., Salgueiro, N., & Mesquita, S. (2018). Impacts of On-shore Wind Farms in Wildlife Communities: Direct Fatalities and Indirect Impacts (Behavioural and Habitat Effects). In M. Mascarenhas, A. T. Marques, R. Ramalho, D. Santos, J. Bernardino, & C. Fonseca (Eds.), *Biodiversity and Wind Farms in Portugal: Current knowledge and insights for an integrated impact assessment process* (pp. 23–33). Springer International Publishing. https://doi.org/10.1007/978-3-319-60351-3_2

petovarga (2023). *Electricity generation source types. Energy mix solar, water, fossil, wind, nuclear, coal, gas, biomass, geothermal and battery storage. Natural renewable pollution power plants station resources*. Stock Vector ID: 1936131397. Digital Image. Shutterstock. Web. Standard License, 08.03.23.

Pierrat, E., Barbarossa, V., Núñez, M., Scherer, L., Link, A., Damiani, M., Verones, F., & Dorber, M. (2023). Global water consumption impacts on riverine fish species richness in Life Cycle Assessment. *Science of The Total Environment*, *854*, 158702. https://doi.org/10.1016/j.scitotenv.2022.158702

Poulos, H. M., & Camp, A. E. (2010). Decision Support for Mitigating the Risk of Tree Induced Transmission Line Failure in Utility Rights-of-Way. *Environmental Management*, *45*(2), 217–226. https://doi.org/10.1007/s00267-009-9422-5

Rayner, J. M. V. (1988). Form and Function in Avian Flight. In R. F. Johnston (Ed.), *Current Ornithology* (pp. 1–66). Springer US. https://doi.org/10.1007/978-1-4615-6787-5_1

Reimers, E., Eftestøl, S., Tsegaye, D., & Granum, K. (2020). Reindeer fidelity to high quality winter pastures outcompete power line barrier effects. *Rangifer*, *40*(1), Article 1. https://doi.org/10.7557/2.40.1.4968

Richardson, M. L., Wilson, B. A., Aiuto, D. A. S., Crosby, J. E., Alonso, A., Dallmeier, F., & Golinski, G. K. (2017). A review of the impact of pipelines and power lines on biodiversity and strategies for mitigation. *Biodiversity and Conservation*, *26*(8), 1801–1815. https://doi.org/10.1007/s10531-017-1341-9

Rioux, S., Savard, J.-P., & Gerick, A. (2013). Avian mortalities due to transmission line collisions: A review of current estimates and field methods with an emphasis on applications to the Canadian electric network. *Avian Conservation and Ecology*, *8*(2). https://doi.org/10.5751/ACE-00614-080207

Ritchie, H. (2020). *Sector by sector: Where do global greenhouse gas emissions come from? Published online at OurWorldInData.org.* Our World in Data. https://ourworldindata.org/ghg-emissions-by-sector, accessed 28.12.23.

Rosenbaum, R. K., Georgiadis, S., & Fantke, P. (2018). Uncertainty Management and Sensitivity Analysis. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 271–321). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_11

Rosenbaum, R. K., Hauschild, M. Z., Boulay, A.-M., Fantke, P., Laurent, A., Núñez, M., & Vieira, M. (2018). Life Cycle Impact Assessment. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 167–270). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_10

Rubolini, D., Gustin, M., Bogliani, G., & Garavaglia, R. (2005). Birds and powerlines in Italy: An assessment. *Bird Conservation International*, *15*(2), 131–145. https://doi.org/10.1017/S0959270905000109

Rydell, J., Engström, H., Hedenström, A., Kyed Larsen, J., Pettersson, J., & Green, M. (2012). *The effect of wind power on birds and bats: A synthesis*. Naturvårdsverket.

Sala, S., Amadei, A. M., Beylot, A., & Ardente, F. (2021). The evolution of life cycle assessment in European policies over three decades. *The International Journal of Life Cycle Assessment*, *26*(12), 2295–2314. https://doi.org/10.1007/s11367-021-01893-2

Sánchez-Zapata, J. A., Clavero, M., Carrete, M., DeVault, T. L., Hermoso, V., Losada, M. A., Polo, M. J., Sánchez-Navarro, S., Pérez-García, J. M., Botella, F., Ibáñez, C., & Donázar, J. A. (2016). Effects of Renewable Energy Production and Infrastructure on Wildlife. In R.

Mateo, B. Arroyo, & J. T. Garcia (Eds.), *Current Trends in Wildlife Research* (pp. 97–123). Springer International Publishing. https://doi.org/10.1007/978-3-319-27912-1_5

Schaub, M., & Pradel, R. (2004). Assessing the Relative Importance of Different Sources of Mortality from Recoveries of Marked Animals. *Ecology*, *85*(4), 930–938. https://doi.org/10.1890/03-0012

Scherer, L., Rosa, F., Sun, Z., Michelsen, O., De Laurentiis, V., Marques, A., Pfister, S., Verones, F., & Kuipers, K. J. J. (2023). Biodiversity Impact Assessment Considering Land Use Intensities and Fragmentation. *Environmental Science & Technology*, *57*(48), 19612–19623. https://doi.org/10.1021/acs.est.3c04191

Scholz, Y., Gils, H. C., & Pietzcker, R. C. (2017). Application of a high-detail energy system model to derive power sector characteristics at high wind and solar shares. *Energy Economics*, *64*, 568–582. https://doi.org/10.1016/j.eneco.2016.06.021

SD. (2013). *Meld. St. 26 (2012–2013)—Nasjonal transportplan 2014–2023*. Samferdselsdepartementet (SD). https://www.regjeringen.no/no/dokumenter/meld-st-26-20122013/id722102/

Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., & Malley, J. (Eds.). (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* https://doi.org/10.1017/9781009157926

Simensen, T., A'Campo, W., Atakan, A., Heggdal, J. E., Aune-Lundberg, L., Vagnildhaug, A., Kristensen, Ø., & Lindaas, G. O. (2023). Planlagt utbyggingsareal i Norge. Identifisering av mulig framtidig utbyggingsareal i kommunale arealplaner etter plan- og bygningsloven. NINA Rapport 2310. Norsk institutt for naturforskning (NINA). https://hdl.handle.net/11250/3085779

Skarin, A., & Åhman, B. (2014). Do human activity and infrastructure disturb domesticated reindeer? The need for the reindeer's perspective. *Polar Biology*, *37*(7), 1041–1054. https://doi.org/10.1007/s00300-014-1499-5

Škorpíková, V., Hlaváč, V., & Křápek, M. (2019). Bird mortality on medium-voltage power lines in the Czech Republic. *Raptor Journal*, *13*(1), 27–44. https://doi.org/10.2478/srj-2019-0007

SSB. (2023a). *08307: Produksjon, import, eksport og forbruk av elektrisk kraft (GWh) 1950 - 2022*. Statistisk sentralbyrå (SSB). https://www.ssb.no/statbank/table/08307, accessed 24.01.24.

SSB. (2023b). *09469: Nettoproduksjon av fjernvarme, etter varmesentral, statistikkvariabel og år. Statistikkbanken*. Statistisk sentralbyrå (SSB). https://www.ssb.no/statbank/table/09469, accessed 24.01.24.

Statnett. (2022). *Derfor har vi prisområder for strøm i Norge*. Derfor har vi prisområder. https://www.statnett.no/om-statnett/bli-bedre-kjent-med-statnett/om-strompriser/fakta-om-prisomrader/, accessed 01.12.23.

Statnett. (2023a). *Analyse av transportkanaler 2023-2050*. https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/analyse-av-transportkanaler/

Statnett. (2023b). *Langsiktig markedsanalyse—Norge, Norden og Europa 2022-2050*. https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/langsiktig-markedsanalyse/

Statnett. (2023c). *Systemutviklingsplan 2023*. https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/systemutviklingsplan/

Steinert, M., Eldegard, K., Sydenham, M. A. K., & Moe, S. R. (2021). Bumble bee communities in power-line clearings: Effects of experimental management practices. *Insect Conservation and Diversity*, *14*(3), 377–392. https://doi.org/10.1111/icad.12463

Storm, J. J., & Choate, J. R. (2012). Structure and Movements of a Community of Small Mammals Along a Powerline Right-Of-Way in Subalpine Coniferous Forest. *The Southwestern Naturalist*, *57*(4), 385–392. https://doi.org/10.1894/0038-4909-57.4.385

Tella, J. L., Hernández-Brito, D., Blanco, G., & Hiraldo, F. (2020). Urban Sprawl, Food Subsidies and Power Lines: An Ecological Trap for Large Frugivorous Bats in Sri Lanka? *Diversity*, *12*(3), Article 3. https://doi.org/10.3390/d12030094

Tellefsen, T., van Putten, J., & Gjerde, O. (2020). Norwegian Hydropower: Connecting to Continental Europe. *IEEE Power and Energy Magazine*, *18*(5), 27–35. https://doi.org/10.1109/MPE.2020.3001417

Tintó, A., Real, J., & Mañosa, S. (2010). Predicting and Correcting Electrocution of Birds in Mediterranean Areas. *The Journal of Wildlife Management*, *74*(8), 1852–1862. https://doi.org/10.2193/2009-521

Ueckerdt, F., Pietzcker, R., Scholz, Y., Stetter, D., Giannousakis, A., & Luderer, G. (2017). Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. *Energy Economics*, *64*, 665–684. https://doi.org/10.1016/j.eneco.2016.05.012

UNEP. (2016). *Green Energy Choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production. Report of the International Resource Panel.* E.G. Hertwich, J. Aloisi de Larderel, A.

Arvesen, P. Bayer, J. Bergesen, E. Bouman, T. Gibon, G. Heath, C. Peña, P. Purohit, A. Ramirez, S. Suh, (eds.) https://www.resourcepanel.org/reports/green-energy-choices-benefits-risks-and-trade-offs-low-carbon-technologies-electricity

van Treeck, R., Geist, J., Pander, J., Tuhtan, J., & Wolter, C. (2022). Impacts and Risks of Hydropower. In P. Rutschmann, E. Kampa, C. Wolter, I. Albayrak, L. David, U. Stoltz, & M. Schletterer (Eds.), *Novel Developments for Sustainable Hydropower* (pp. 41–60). Springer International Publishing. https://doi.org/10.1007/978-3-030-99138-8_4

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A., Liao, X., Lindner, J. P., Maia de Souza, D., Michelsen, O., Patouillard, L., Pfister, S., Posthuma, L., Prado, V., Ridoutt, B., Rosenbaum, R. K., … Fantke, P. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. *Journal of Cleaner Production*, *161*, 957–967. https://doi.org/10.1016/j.jclepro.2017.05.206

Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N., Cucurachi, S., de Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., Heijungs, R., Jolliet, O., Juraske, R., Larsen, H., Laurent, A., Mutel, C. L., Margni, M., … Huijbregts, M. A. J. (2020). LC-IMPACT: A regionalized life cycle damage assessment method. *Journal of Industrial Ecology*, *24*(6), 1201–1219. https://doi.org/10.1111/jiec.13018

Verones, F., Kuipers, K., Núñez, M., Rosa, F., Scherer, L., Marques, A., Michelsen, O., Barbarossa, V., Jaffe, B., Pfister, S., & Dorber, M. (2022). Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment. *Ecological Indicators*, *142*, 109204. https://doi.org/10.1016/j.ecolind.2022.109204

Vistnes, I., & Nellemann, C. (2001). Avoidance of Cabins, Roads, and Power Lines by Reindeer during Calving. *The Journal of Wildlife Management*, *65*(4), 915–925. https://doi.org/10.2307/3803040

Vistnes, I., & Nellemann, C. (2008). The matter of spatial and temporal scales: A review of reindeer and caribou response to human activity. *Polar Biology*, *31*(4), 399–407. https://doi.org/10.1007/s00300-007-0377-9

Wagner, D. L., Metzler, K. J., & Frye, H. (2019). Importance of transmission line corridors for conservation of native bees and other wildlife. *Biological Conservation*, *235*, 147–156. https://doi.org/10.1016/j.biocon.2019.03.042

Winter, L., Lehmann, A., Finogenova, N., & Finkbeiner, M. (2017). Including biodiversity in life cycle assessment – State of the art, gaps and research needs. *Environmental Impact Assessment Review*, *67*, 88–100. https://doi.org/10.1016/j.eiar.2017.08.006

Woods, J. S., Damiani, M., Fantke, P., Henderson, A. D., Johnston, J. M., Bare, J., Sala, S., Maia de Souza, D., Pfister, S., Posthuma, L., Rosenbaum, R. K., & Verones, F. (2018). Ecosystem quality in LCIA: Status quo, harmonization, and suggestions for the way forward. *The International Journal of Life Cycle Assessment*, *23*(10), 1995–2006. https://doi.org/10.1007/s11367-017-1422-8

Zarfl, C., Berlekamp, J., He, F., Jähnig, S. C., Darwall, W., & Tockner, K. (2019). Future large hydropower dams impact global freshwater megafauna. *Scientific Reports*, *9*(1), Article 1. https://doi.org/10.1038/s41598-019-54980-8

2.

BETWEEN THE LINES: LIFE CYCLE IMPACT ASSESSMENT MODELS OF COLLISION AND ELECTROCUTION IMPACTS OF POWER LINES ON BIRD DIVERSITY IN NORWAY

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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

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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 8.48×10^{-16} and 5.6×10^{-15} PDF*yr/kWh for collision and 3.27×10^{-18} and 1.66×10^{-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).

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

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_{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):

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

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 ± 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 (1×10^{-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 1×1 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 (1×1 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 10×10 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

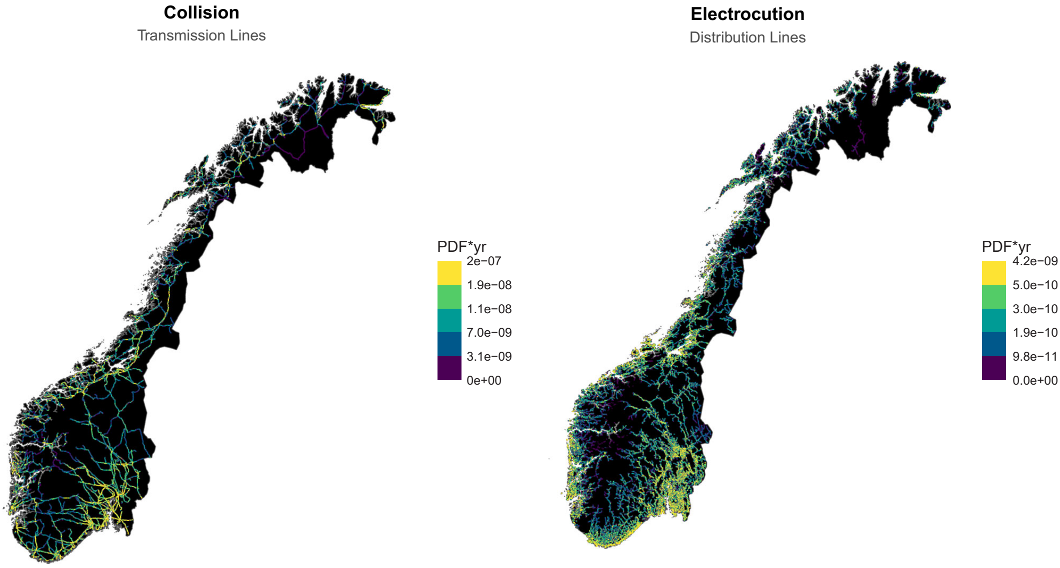

FIGURE 1 Potentially disappeared fraction of species results for collision with transmission lines (left) and electrocution by distribution lines (right) impact pathways in Norway. Underlying data for this figure are available in the Zenodo repository.

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 3.17×10^{-4} PDF*yr, while the distribution lines resulted in a yearly impact of 5.86×10^{-4} PDF*yr. For electrocution, the high-voltage pylons had a PDF*yr of 1.38×10^{-6}, and the low-voltage pylons had a PDF*yr of 1.65×10^{-5}. The collision impact varied from 1.6×10^{-15} to 2.03×10^{-7} PDF*yr for transmission lines and from 8.83×10^{-16} to 1.41×10^{-7} PDF*yr for distribution lines. The electrocution impacts ranged from 1.67×10^{-12} to 2×10^{-9} PDF*yr for transmission lines and from 4.1×10^{-12} to 4.21×10^{-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 8.48×10^{-16} and 5.6×10^{-15} PDF*yr/kWh, while for electrocution, they ranged between 3.27×10^{-18} and 1.66×10^{-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).

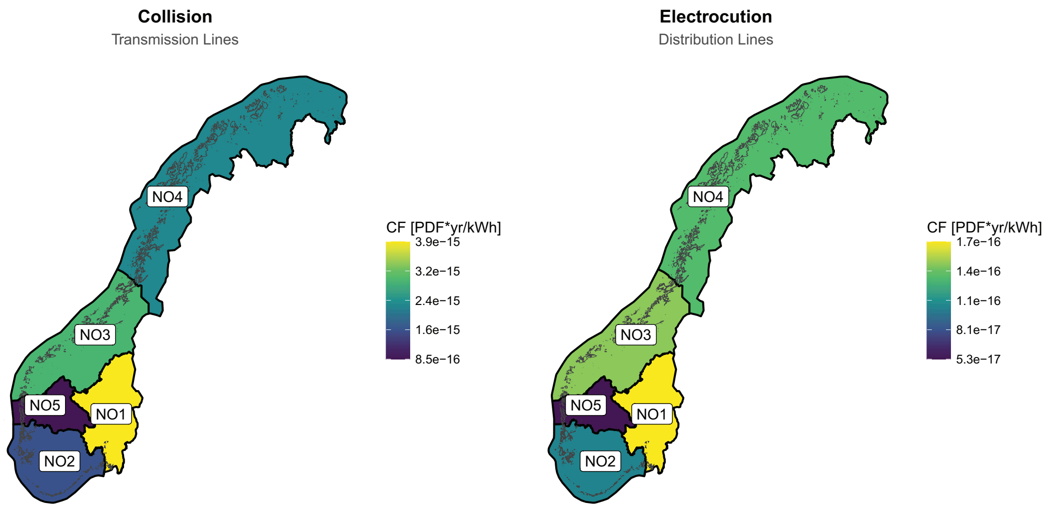

FIGURE 2 Characterization factors quantifying the impact of electricity consumption on bird richness in potentially disappeared fraction of species*yr/kWh due to collision with transmission lines (left) and electrocution by distribution lines (right). Underlying data for this figure are available in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

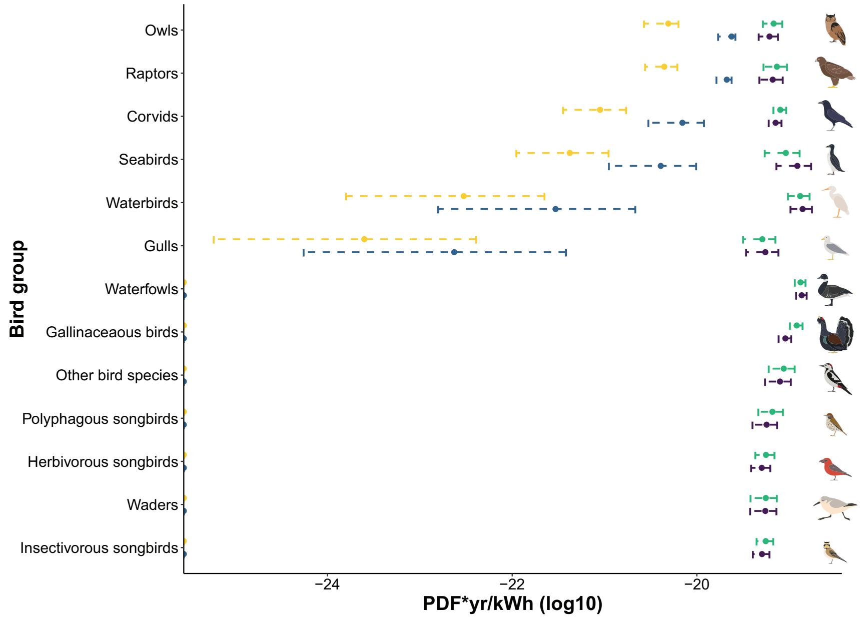

FIGURE 3 Potentially disappeared fraction of species of species richness per bird group per electricity production and consumption (kWh) for collision impact pathway with transmission lines (green line) and distribution lines (purple line) and for electrocution by transmission lines (yellow line) and 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.

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REFERENCES

APLIC. (2006). *Suggested practices for avian protection on power lines: the state of the art in 2006*. Edison Electric Institute, Avian Power Line Interaction Committee (APLIC), and the California Energy Commission. Washington, D.C and Sacramento, CA.

APLIC. (2012). *Reducing avian collisions with power lines: The state of the art in 2012*. Edison Electric Institute and Avian Power Lines Interaction Committee (APLIC). Washington, D.C.

Arderne, C., Zorn, C., Nicolas, C., & Koks, E. E. (2020). Predictive mapping of the global power system using open data. *Scientific Data*, *7*(1), 1–12. https://doi.org/10.1038/s41597-019-0347-4

Barrientos, R., Ponce, C., Palacín, C., Martín, C. A., Martín, B., & Alonso, J. C. (2012). Wire marking results in a small but significant reduction in avian mortality at power lines: A BACI designed study. *PLoS ONE*, *7*(3), e32569. https://doi.org/10.1371/journal.pone.0032569

Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J. F., Marques, A. T., Martins, R. C., Shaw, J. M., Silva, J. P., & Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation*, *222*, 1–13. https://doi.org/10.1016/j.biocon.2018.02.029

Bernshausen, F., Kreuziger, J., Krimkowski, J., Menzel, A., & Rösner, B. (2017). *Vogel-Kollisionsopfer an Hoch- und Höchstspannungsfreileitungen in Deutschland—Eine Abschätzung*. TNL Umweltplanung, Hungen.

Bevanger, K. (1998). Biological and conservation aspects of bird mortality caused by electricity power lines: A review. *Biological Conservation*, *86*(1), 67–76. https://doi.org/10.1016/S0006-3207(97)00176-6

Bevanger, K., Bartzke, G., Broseth, H., Gjershaug, J. O., Hanssen, F., Jacobsen, K., Kvaloy, P., May, R., Nygard, T., Pedersen, H. C., Reitan, O., Refsnaes, S., Stokke, S., & Vang, R. (2010). Optimal design and routing of power lines; ecological, technical and economic perspectives (OPTIPOL). Progress Report 2010. NINA Report 619. http://hdl.handle.net/11250/2642541

Biasotto, L. D., & Kindel, A. (2018). Power lines and impacts on biodiversity: A systematic review. *Environmental Impact Assessment Review*, *71*, 110–119. https://doi.org/10.1016/j.eiar.2018.04.010

Biasotto, L. D., Moreira, F., Bencke, G. A., D'Amico, M., Kindel, A., & Ascensão, F. (2022). Risk of bird electrocution in power lines: A framework for prioritizing species and areas for conservation and impact mitigation. *Animal Conservation*, *25*(2), 285–296. https://doi.org/10.1111/acv.12736

Bjørn, A., Owsianiak, M., Molin, C., & Alexis, L. (2018). Main characteristics of LCA. In Hauschild, M., Rosenbaum, R., & Olsen, S. (Eds), *Life cycle assessment*. Springer. https://doi.org/10.1007/978-3-319-56475-3_2

Bruderer, B., & Boldt, A. (2001). Flight characteristics of birds: I. Radar measurements of speeds. *Ibis*, *143*(2), 178–204. https://doi.org/10.1111/j.1474-919X.2001.tb04475.x

Buchhorn, M., Smets, B., Bertels, L., de Roo, B., Lesiv, M., Tsendbazar, N.-E., Herold, M., & Fritz, S. (2020). Copernicus global land service: Land cover 100m: Collection 3: Epoch 2019: Globe (V3.0.1). *Zenodo*, https://doi.org/10.5281/zenodo.3939050

Chaudhary, A., Verones, F., de Baan, L., & Hellweg, S. (2015). Quantifying land use impacts on biodiversity: Combining species-area models and vulnerability indicators. *Environmental Science and Technology*, *49*(16), 9987–9995. https://doi.org/10.1021/acs.est.5b02507

Cornell Lab of Ornithology. (2021). All about birds. https://www.allaboutbirds.org/

D'Amico, M., Martins, R. C., Álvarez-Martínez, J. M., Porto, M., Barrientos, R., & Moreira, F. (2019). Bird collisions with power lines: Prioritizing species and areas by estimating potential population-level impacts. *Diversity and Distributions*, *25*(6), 975–982. https://doi.org/10.1111/ddi.12903

Dorber, M., Kuipers, K., & Verones, F. (2020). Global characterization factors for terrestrial biodiversity impacts of future land inundation in life cycle assessment. *Science of The Total Environment*, *712*, 134582. https://doi.org/10.1016/j.scitotenv.2019.134582

Dorber, M., Mattson, K. R., Sandlund, O. T., May, R., & Verones, F. (2019). Quantifying net water consumption of Norwegian hydropower reservoirs and related aquatic biodiversity impacts in life cycle assessment. *Environmental Impact Assessment Review*, *76*(7491), 36–46. https://doi.org/10.1016/j.eiar.2018.12.002

DSB. (2006). *Veiledning til forskrift om elektriske forsyningsanlegg*. Direktoratet for samfunnssikkerhet og beredskap (DSB). https://www.dsb.no/lover/elektriske-anlegg-og-elektrisk-utstyr/veiledning-til-forskrift/veiledning-til-forskrift-om-elektriske-forsyningsanlegg/

Dwyer, J. F., Gerber, B. D., Petersen, P., Armstrong, W. E., & Harness, R. E. (2020). Power pole density and avian electrocution risk in the Western United States. *Journal of Raptor Research*, *54*(2), 93–109. https://doi.org/10.3356/0892-1016-54.2.93

Dwyer, J. F., Harness, R. E., & Donohue, K. (2014). Predictive model of avian electrocution risk on overhead power lines. *Conservation Biology*, *28*(1), 159–168. https://doi.org/10.1111/cobi.12145

Dwyer, J. F., Harness, R. E., Gerber, B. D., Landon, M. A., Petersen, P., Austin, D. D., Woodbridge, B., Williams, G. E., & Eccleston, D. (2016). Power pole density informs spatial prioritization for mitigating avian electrocution. *Journal of Wildlife Management*, *80*(4), 634–642. https://doi.org/10.1002/jwmg.1048

Eccleston, D., Groh, N., Harness, R., Petersen, P., Brockbank, R., & Rogers, T. (2023). Ignition prevention on overhead powerlines: Assessing and mitigating risk from wildlife. In L. Denney & N. G. Pupa (Eds.), *Environmental concerns in rights-of-way management 13th international symposium* (pp. 383–391). Pique Publishing, Inc.

Eccleston, D., & Harness, R. (2018). Raptor electrocutions and power line collisions. In J. H. Sarasola, J. M. Grande, & J. J. Negro (Eds.), *Birds of prey. Biology and conservation in the XXI century* (pp. 273–302). Springer. https://doi.org/10.1007/978-3-319-73745-4_12

ENTSO-E. (2021). *Ten-Year Network Development Plan (TYNDP) 2020 - Main report.* January 2021 - Version for ACER opinion.

ENTSO-E. (2022). *ENTSO-E transparency platform*. https://transparency.entsoe.eu/

EU Copernicus Land Monitoring Service. (2018). *Tree cover density—High resolution layers*. European Environment Agency (EEA). https://doi.org/10.2909/486f77da-d605-423e-93a9-680760ab6791

Gális, M., Naďo, L., Hapl, E., Šmídt, J., Deutschová, L., & Chavko, J. (2020). Comprehensive analysis of bird mortality along power distribution lines in Slovakia. *Raptor Journal*, *13*(1), 1–25. https://doi.org/10.2478/srj-2019-0006

Gargiulo, A., Girardi, P., & Temporelli, A. (2017). LCA of electricity networks: A review. *International Journal of Life Cycle Assessment*, *22*(10), 1502–1513. https://doi.org/10.1007/s11367-017-1279-x

Guil, F., & Pérez-García, J. M. (2022). Bird electrocution on power lines: Spatial gaps and identification of driving factors at global scales. *Journal of Environmental Management*, *301*, 113890. https://doi.org/10.1016/j.jenvman.2021.113890

Hellweg, S., & i Canals, L. M. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science*, *344*(6188), 1109–1113. https://doi.org/10.1126/science.1248361

Hernández-Lambraño, R. E., Sánchez-Agudo, J. Á., & Carbonell, R. (2018). Where to start? Development of a spatial tool to prioritise retrofitting of power line poles that are dangerous to raptors. *Journal of Applied Ecology*, *55*(6), 2685–2697. https://doi.org/10.1111/1365-2664.13200

IEA. (2021). *World Energy Outlook 2021*. IParis, France. https://www.iea.org/reports/world-energy-outlook-2021

ISO. (2006). *ISO 14044: Environmental Management—Life Cycle Assessment—Principles and Framework*. International Organisation for Standardization (ISO), Geneva, Switzerland.

Janss, G. F. E. (2000). Avian mortality from power lines: A morphologic approach of a species-specific mortality. *Biological Conservation*, *95*(3), 353–359. https://doi.org/10.1016/S0006-3207(00)00021-5

KMD. (2015). *Meld. St. 14 (2015–2016)— Natur for livet - Norsk handlingsplan for naturmangfold*. Klima og miljødepartement (KMD). https://www.regjeringen.no/no/dokumenter/meld.-st.-14-20152016/id2468099/

Kolnegari, M., Conway, G. J., Basiri, A. A., Panter, C. T., Hazrati, M., Rafiee, M. S., Ferrer, M., & Dwyer, J. F. (2021). Electrical components involved in avian-caused outages in Iran. *Bird Conservation International*, *31*(3), 364–378. https://doi.org/10.1017/S0959270920000507

Kuipers, K. J. J., May, R., & Verones, F. (2021). Considering habitat conversion and fragmentation in characterisation factors for land-use impacts on vertebrate species richness. *Science of The Total Environment*, *801*(89), 149737. https://doi.org/10.1016/j.scitotenv.2021.149737

Ladle, R. J., & Whittaker, R. J. (2011). Conservation biogeography. *Conservation Biogeography*, pp. 1–301. Blackwell Publishing Ltd. https://doi.org/10.1002/9781444390001

Laurent, A., Espinosa, N., & Hauschild, M. Z. (2018). LCA of energy systems. In Hauschild, M., Rosenbaum, R., & Olsen, S. (Eds), *Life cycle assessment*. Springer. https://doi.org/10.1007/978-3-319-56475-3_26

Lawton, J. H. (1999). Are there general laws in ecology? *Oikos*, *84*(2), 177–192. https://doi.org/10.2307/3546712

Lehman, R. N., Kennedy, P. L., & Savidge, J. A. (2007). The state of the art in raptor electrocution research: A global review. *Biological Conservation*, *136*(2), 159–174. https://doi.org/10.1016/j.biocon.2006.09.015

Lislevand, T., Figuerola, J., & Székely, T. (2007). Avian body sizes in relation to fecundity, mating system, display behavior, and resource sharing. *Ecological Archive*, *88*(6), 1605. https://doi.org/10.1890/06-2054

Lomolino, M. V. (2000). Ecology's most general, yet protean pattern: The species-area relationship. *Journal of Biogeography*, *27*(1), 17–26. http://www.jstor.org/stable/2655979

Loss, S. R., Will, T., & Marra, P. P. (2014). Refining estimates of bird collision and electrocution mortality at power lines in the United States. *PLoS ONE*, *9*(7), 26–28. https://doi.org/10.1371/journal.pone.0101565

Martin, G. R. (2011). Understanding bird collisions with man-made objects: A sensory ecology approach. *Ibis*, *153*(2), 239–254. https://doi.org/10.1111/j.1474-919X.2011.01117.x

Martin, G. R., & Shaw, J. M. (2010). Bird collisions with power lines: Failing to see the way ahead? *Biological Conservation*, *143*(11), 2695–2702. https://doi.org/10.1016/j.biocon.2010.07.014

May, R., Jackson, C. R., Middel, H., Stokke, B. G., & Verones, F. (2021). Life-cycle impacts of wind energy development on bird diversity in Norway. *Environmental Impact Assessment Review*, *90*, 106635. https://doi.org/10.1016/j.eiar.2021.106635

May, R., Middel, H., Stokke, B. G., Jackson, C., & Verones, F. (2020). Global life-cycle impacts of onshore wind-power plants on bird richness. *Environmental and Sustainability Indicators*, *8*, 100080. https://doi.org/10.1016/j.indic.2020.100080

Nord University. (2021). *BirdID's bird guide*. https://quiz.natureid.no/bird/eBook.php

NVE. (2016). *Skogrydding i kraftledningstraséer. Forsyningssikkerhet, miljø- og landskapshensyn*. https://www.nve.no/energi/tilsyn/nytt-fra-miljoetilsynet/ny-veileder-om-skogrydding-i-kraftledningstraseer/

NVE. (2020). *Langsiktig kraftmarkedsanalyse 2020–2040. Mer fornybar kraftproduksjon gir mer væravhendige kraftpriser*.

NVE. (2021). *Nedlasting av fagdata fra NVE*. https://nedlasting.nve.no/gis/

OED. (2021). *Meld. St. 36 (2020-2021). Melding til Stortinget. In: Energi til arbeid—Langsiktig verdiskaping fra norske energiressurser*. Olje og energidepartementet (OED). https://www.regjeringen.no/no/dokumenter/meld.-st.-36-20202021/id2860081/

Oiseaux. (2021). *Les Oiseaux*. https://www.oiseaux.net/

Owsianiak, M., Bjørn, A., Laurent, A., Molin, C., & Ryberg, M. W. (2018). LCA applications. In Hauschild, M., Rosenbaum, R., & Olsen, S. (Eds), *Life cycle assessment: Theory and practice* (pp. 31–41). Springer. https://doi.org/10.1007/978-3-319-56475-3_4

Paquet, J. Y., Swinnen, K., Derouaux, A., Devos, K., & Verbelen, D. (2022). Sensitivity mapping informs mitigation of bird mortality by collision with high-voltage power lines. *Nature Conservation*, *47*, 215–233. https://doi.org/10.3897/natureconservation.47.73710

Pavón-Jordán, D., Stokke, B. G., Åström, J., Bevanger, K., Hamre, Ø., Torsæter, E., & May, R. (2020). Do birds respond to spiral markers on overhead wires of a high-voltage power line? Insights from a dedicated avian radar. *Global Ecology and Conservation*, *24*, e01363. https://doi.org/10.1016/J.GECCO.2020.E01363

Pennycuick, C. J. (2008). Chapter 5 The feathered wings of birds. *Theoretical Ecology Series*, *5*, 105–134. https://doi.org/10.1016/S1875-306X(08)00005-1

Pérez-García, J. M., Botella, F., Sánchez-Zapata, J. A., & Moleón, M. (2011). Conserving outside protected areas: Edge effects and avian electrocutions on the periphery of special protection areas. *Bird Conservation International*, *21*(3), 296–302. https://doi.org/10.1017/S0959270911000062

Pérez-García, J. M., DeVault, T. L., Botella, F., & Sánchez-Zapata, J. A. (2017). Using risk prediction models and species sensitivity maps for large-scale identification of infrastructure-related wildlife protection areas: The case of bird electrocution. *Biological Conservation*, *210*, 334–342. https://doi.org/10.1016/j.biocon.2017.04.033

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017). Opening the black box: An open-source release of Maxent. *Ecography*, *40*(7), 887–893. https://doi.org/10.1111/ECOG.03049

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.r-project.org/

Rayner, J. M. V. (1988). Form and function in avian flight. In R. F. Johnston (Ed.), *Current Ornithology* (pp. 1–66). Springer. https://doi.org/10.1007/978-1-4615-6787-5_1

Richardson, M. L., Wilson, B. A., Aiuto, D. A. S., Crosby, J. E., Alonso, A., Dallmeier, F., & Golinski, G. K. (2017). A review of the impact of pipelines and power lines on biodiversity and strategies for mitigation. *Biodiversity and Conservation*, *26*(8), 1801–1815. https://doi.org/10.1007/s10531-017-1341-9

Rioux, S., Savard, J. P. L., & Gerick, A. A. (2013). Avian mortalities due to transmission line collisions: A review of current estimates and field methods with an emphasis on applications to the Canadian electric network. *Avian Conservation and Ecology*, *8*(2), 7. https://doi.org/10.5751/ACE-00614-080207

Rosenzweig, M. L. (1995). *Species diversity in space and time*. Cambridge University Press. https://doi.org/10.1017/CBO9780511623387

Rosvold, K. A. (2019). *ledningsmast i Store norske leksikon på snl.no*. https://snl.no/ledningsmast

Rubolini, D., Gustin, M., Bogliani, G., & Garavaglia, R. (2005). Birds and powerlines in Italy: An assessment. *Bird Conservation International*, *15*(2), 131–145. https://doi.org/10.1017/S0959270905000109

Shaw, J. M., Reid, T. A., Schutgens, M., Jenkins, A. R., & Ryan, P. G. (2018). High power line collision mortality of threatened bustards at a regional scale in the Karoo, South Africa. *Ibis*, *160*(2), 431–446. https://doi.org/10.1111/IBI.12553

Sicacha-Parada, J., Pavon-Jordan, D., Steinsland, I., May, R., Stokke, B., & Norway, T. (2023). *New spatial models for integrating standardized detection-nondetection and opportunistic presence-only data: Application to estimating risk factors associated to powerline-induced death of birds*. https://doi.org/10.48550/arXiv.2303.02088

Škorpíková, V., Hlaváč, V., & Křápek, M. (2019). Bird mortality on medium voltage power lines in the Czech Republic. *Raptor Journal*, *13*(1), 27–44. https://doi.org/10.2478/srj-2019-0007

SSB. (2022). *Statistics Norway - 10314: Nettoforbruk av elektrisk kraft, etter forbrukergruppe (GWh) (K) 2010 - 2022*. https://www.ssb.no/statbank/table/10314

Statnett. (2022). *Derfor har vi prisområder for strøm i Norge*. https://www.statnett.no/om-statnett/bli-bedre-kjent-med-statnett/om-strompriser/fakta-om-prisomrader/

Storch, D., Keil, P., & Jetz, W. (2012). Universal species–area and endemics–area relationships at continental scales. *Nature*, *488*(7409), 78–81. https://doi.org/10.1038/nature11226

Tintó, A., Real, J., & Mañosa, S. (2010). Predicting and correcting electrocution of birds in Mediterranean areas. *Journal of Wildlife Management*, *74*(8), 1852–1862. https://doi.org/10.2193/2009-521

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A., Liao, X., Lindner, J. P., de Souza, D., Michelsen, O., Patouillard, L., Pfister, S., Posthuma, L., Prado, V., Ridoutt, B., Rosenbaum, R. K., … Fantke, P. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC life cycle initiative. *Journal of Cleaner Production*, *161*, 957–967. https://doi.org/10.1016/j.jclepro.2017.05.206

Vincze, O., Vágási, C. I., Pap, P. L., Palmer, C., & Møller, A. P. (2019). Wing morphology, flight type and migration distance predict accumulated fuel load in birds. *Journal of Experimental Biology*, *222*(1), 4–10. https://doi.org/10.1242/jeb.183517

Wilman, H., Belmaker, J., Simpson, J., de la Rosa, C., Rivadeneira, M. M., & Jetz, W. (2014). EltonTraits 1.0: Species-level foraging attributes of the world's birds and mammals. *Ecology*, *95*(7), 2027. https://doi.org/10.1890/13-1917.1

Woods, J. S., Damiani, M., Fantke, P., Henderson, A. D., Johnston, J. M., Bare, J., Sala, S., de Souza, D., Pfister, S., Posthuma, L., Rosenbaum, R. K., & Verones, F. (2018). Ecosystem quality in LCIA: Status quo, harmonization, and suggestions for the way forward. *The International Journal of Life Cycle Assessment*, *23*, 1995–2006. https://doi.org/10.1007/S11367-017-1422-8

Bruderer, B., Peter, D., Boldt, A., & Liechti, F. (2010). Wing-beat characteristics of birds recorded with tracking radar and cine camera. Ibis, 152(2), 272–291. https://doi.org/10.1111/j.1474-919X.2010.01014.x

Billerman, S.M., Keeney, B.K., Rodewald, P.G. & Schulenberg, T.S. (Eds.). (2022). Birds of the world. Cornell Laboratory of Ornithology. https://birdsoftheworld.org/bow/

SUPPORTING INFORMATION

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

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3.

BIODIVERSITY ON THE LINE: LIFE CYCLE IMPACT ASSESSMENT OF POWER LINES ON SPECIES RICHNESS

In review. The Journal of Environment Research: Infrastructure and Sustainability.

This paper is awaiting publication and is not included in NTNU Open

4.

QUANTIFYING GLOBAL POWERLINES IMPACTS ON BIRDS AND MAMMALS

Environmental Concerns in Rights-of-Way Management 13th International Symposium (2023). Pique Publishing, Inc: 37–72.

Quantifying Global Powerlines Impacts on Birds and Mammals

Dafna Gilad, Roel May, and Francesca Verones

There is an expected increase in the global electricity demand. Furthermore, decarbonization and electrification will rapidly expand the current grid network. However, constructing more transmission and distribution lines may impact biodiversity through habitat loss, fragmentation, disturbance, and mortality of birds by collision and electrocution. Life cycle assessment is a common framework to analyze environmental impacts and assist policymakers in reducing potential impacts. However, existing life cycle assessment methods do not yet address the effects of powerlines on biodiversity. We developed a global approach to quantify the habitat loss impact of powerlines on mammals and birds based on the potentially disappeared fraction of species. We calculated how species richness is affected by the current energy distribution system. We identified conflict hotspots, demonstrating the importance of including a spatial component in these assessments. Our model can support sustainable decision-making in future planning of electricity grid networks to reduce the ongoing pressure on biodiversity and ecosystems.

Keywords: Biodiversity, Geospatial, Habitat Loss Impact, Human Use/Impact, Life Cycle Assessment (LCA), Powerlines, Rights-of-Way (ROW), Utility Lines.

Environmental Concerns in Rights-of-Way Management
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INTRODUCTION

Among the 17 Sustainable Development Goals (SDG), the seventh goal focuses on ensuring everyone the access to clean, affordable, and reliable energy (UN 2021). Two key elements in promoting this SDG are energy production from renewable sources and electrification (IEA 2021). The replacement of fossil fuels with renewable energy and the electrification of heating and transport systems can reduce emissions and play an important role in mitigating climate change (IPCC 2022). Therefore, a successful energy transition is highly dependent on an extensive, modern electricity grid network: transmission lines must cross the long distances between new renewable energy power plants to local powerlines, while distribution lines are required for increasing electricity access and ensuring stable and reliable delivery of energy (IEA 2021).

However, further development of the global electricity grid may sabotage the accomplishments of SDG 15 (Life on Land). Trees and shrubs underneath powerlines are removed to ensure access and to protect infrastructure from the risk of outages. The width of the linear clearing area, also known as the rights-of-way (ROW), can reach up to 100 m. Although powerlines are common along roads and in cities, they are also constructed through diverse landscapes and affect natural habitats (Latham and Boutin 2015). Powerlines cause habitat fragmentation, modification, and loss (Bartzke et al. 2014; Gracey and Verones 2016). In addition, their construction disturbs animals (Biasotto and Kindel 2018) and puts birds worldwide at risk of collision and electrocution (Richardson et al. 2017; Bernardino et al. 2018; Biasotto and Kindel 2018). Nevertheless, expanding powerline networks seems inevitable, as the share of energy production from renewable sources, decarbonization, and electricity demand is expected to increase rapidly (IEA 2021).

An environmental impact assessment framework is necessary to evaluate the numerous biodiversity impacts of electricity distribution to ensure sustainable electrical grid development while minimizing its effect on ecosystems. Life cycle assessment (LCA) is a method that quantifies such potential environmental impacts to support policymakers' decisions. It is a powerful instrument in designing energy policies (Hellweg and Milá i Canals 2014). Life cycle assessment focuses on the different life stages of a product or a service, from the extraction of raw materials, production, and consumption until its disposal (ISO 14044 2006). An LCA analysis quantifies the amounts of consumed resources and released emissions throughout the lifetime of the product or service (Hellweg and Milá i Canals 2014). The so-called characterization factors indicate the impact of one unit of emission or resource use (e.g., per kg of CO_2 emitted or m_2 of land converted). They subsequently help to calculate the environmental consequences of these emissions and resource uses. For example, we can calculate the impact of habitat loss per kilowatt-hour (kWh) produced or consumed for a certain product or service. Life cycle assessment can simultaneously quantify impacts across several categories and identify trade-offs (Hellweg and Milá i Canals 2014) (i.e., between climate change and biodiversity conservation). Life cycle assessment models can also account for spatial regionalization (Verones et al. 2017) and evaluate impacts based on where they occur geographically and which species they damage.

Powerlines were the center of several LCA studies, as highlighted in the review of Gargiulo et al. (2017). They explored their components, different voltage networks, and the construction and operation phases. Climate change, eutrophication aquatic, and resource depletion were the most frequent impact categories. However, potential impacts on ecosystem quality were neglected (Gargiulo et al. 2017) due to a lack of models. While recently developed LCA models quantify the potential biodiversity impacts of electricity production (e.g., hydropower) (Dorber et al. 2019, 2020) and onshore wind power (May et al. 2020, 2021), they exclude impacts from powerlines.

We present in this study a new methodology to quantify the current habitat loss impacts of powerlines on biodiversity. We applied our method on a global country scale to show how the conversion of forested habitats to linear clearings affects the biodiversity of mammals and birds.

METHODS

Derivation of Characterization Factors for Powerlines Related to Habitat Loss

Potentially Disappeared Species

We calculated characterization factors with a countryside species-area relationship (SAR) model, following the approach suggested in Chaudhary et al. (2015) to quantify the impacts of land use changes. Species-area relationship describes the relationship between the area of habitat and the number of species it can support. It assumes that species richness depends on the habitat size (i.e., a larger habitat can sustain more species) (Conor and McCoy 2013). A classic SAR would convert any modified habitat into hostile habitat (i.e., loss of all species), while a countryside SAR assumes that species can survive in modified landscapes

(Chaudhary et al. 2015). Here, the countryside SAR model predicts how many species potentially disappear (potentially disappeared fraction - PDF_j), i.e., become locally extinct, within each ecoregion *j* due to land use change (Eq. (1)).

$$\text{PDF}_{t,p,j} = 1 - \left(\frac{A_{new,p,j} + h_{t,j} \times A_{lost,p,j}}{A_{org,j}}\right)^{z_j} \quad (1)$$

$A_{org,j}$ [m^2] accounts for the original area size of each ecoregion *j*. $A_{new,p,j}$ [m^2] represents the remaining habitat after the construction of the ROW, while $A_{lost,p,j}$ [m^2] is the total area size of the ROW in each ecoregion. We generated PDF values per powerline type *p* to differentiate between transmission and distribution lines. The constant *z* describes the slope of the SAR in ecoregion *j*. We assigned *z* values (Drakare et al. 2006) for each ecoregion by following de Baan et al. (2013), who assigned ecoregions with habitat types (i.e., island, non-forest, and forest). We classified 23 further ecoregions without habitat category by examining their spatial location and ecoregion description.

The affinity ($h_{t,j}$) indicates how sensitive a taxonomic group *t* (mammals or birds) is to the conversion of natural habitat to a modified habitat (i.e., how well they can adapt to living in human-modified landscapes). We assume the affinity (*h*) of a taxonomic group *t* to their natural habitat equals 1. We calculated the affinity for the conversion of natural habitat to ROW with the following equation (Eq. (2)):

$$\text{h}_{t,j} = \left(\frac{S_{t,j}}{S_{org,t,j}}\right)^{1/z_j} \quad (2)$$

The affinity ($h_{t,j}$) is generated by the ratio between the species richness in the modified habitat ($S_{t,j}$) and species richness in the natural habitat ($S_{org,t,j}$). If the natural habitat is converted into a more hostile one, their affinity to such modified habitat decreases to zero. Lower ratios indicate that most species are sensitive to anthropogenic modifications, while higher ratios suggest that many remain in their habitat despite the modification.

We then calculated the regional characterization factors by dividing the PDF values by the area lost within each ecoregion due to the construction of the ROWs (Eq. (3)). The regional characterisation factor represents how many species are lost per m^2.

$$\text{CF}_{\text{regional},t,p,j} = \frac{PDF_{t,p,j}}{A_{lost,p,j}} \quad (3)$$

Aggregation to Country Values

We performed an aggregation step from ecoregions to countries since electricity production and consumption data were only available at the country level. First, we aggregated the ecoregion level characterization factors to the country level by weighting the area size of the ecoregions within each country ($A_{j,c}$) by the total area of the country (A_c) (Eq. (4)).

$$\text{CF}_{regional,t,p,c} = \sum_j CF_{regional,t,p,j} \times \frac{A_{j,c}}{A_c} \quad (4)$$

The final characterization factors were derived by multiplying the regional country-level characterization factors ($CF_{regional,t,p,c}$) by the total ROW's area size within each country ($A_{lost,p,c}$) and by dividing it by the amount of electricity ($E_{p,c}$) produced (transmission lines) or consumed (distribution lines) in each country (Eq. (5)). The regional characterization factors on the country level represent how many species are per lost per production or consumption of one kWh.

$$\text{CF}_{country,t,p} = \frac{CF_{regional,t,p,c} \times A_{lost,p,c}}{E_{p,c}} \quad (5)$$

Eq. (5) is based on the regional PDF of species due to the associated habitat change per m^2 caused by the construction of powerlines. However, the aggregation of regional species loss may lead to an overestimation: if we lose a species locally, it does not necessarily mean that it becomes extinct globally (de Baan et al. 2015). In that case, the global extinction probabilities (GEP) can be used to assess how likely species will become globally extinct if they locally disappear in ecoregion *j*. The GEP considers species distributions, threat levels, and richness to assess the probability of species becoming extinct (Kuipers et al. 2019). Therefore, we multiplied the regional characterization factors with the GEP categories per country (Verones et al. 2022) (Eq. (6)).

$$\text{CF}_{country,t,p,global} = \text{CF}_{country,t,p} \times GEP_c \quad (6)$$

Data

Ecoregion j

We obtained a shapefile of terrestrial ecoregions from WWF (World Wildlife Fund Terrestrial Ecoregions of the World). Ecoregions are defined as large areas with similar species and communities based on biogeographic characterizations (Olson et al. 2001). They are commonly used in LCA as a spatial unit to assess land stress (Verones et al. 2017). We excluded "Rock and Ice" and "Lake" categories as they do not have an ecoregion code and are non-forest habitats.

Species Richness

A species range shapefile for terrestrial mammals (version 6.2) was downloaded from the IUCN (2019) (International Union for Conservation of Nature and Natural Resources). Distribution data for birds (Version 2020.1) were acquired from BirdLife International (2020). We counted the number of species that occur within each ecoregion *j*. For the original species richness ($S_{org,t,j}$), we counted species occurrences with present codes 1 (extant) for 5575 mammals and 10,960 birds. Grassland species ($S_{t,j}$) consist of 1,332 mammals and 2,173 birds that are classified as species in grassland habitats (code 1; extant). All species richness assessments were based on native species only (origin code 1).

ROW Data

We used the global grid network data from the World Bank (Arderne et al. 2020). Transmission and distribution lines were extracted separately. We assumed that the construction of ROW, which requires the removal of all tree cover, would convert the original habitat into an open habitat. Forested areas would reduce their habitat size, yet other habitat types may remain unaffected. Therefore, we reclassified a land cover raster for the year 2019 (Version 3.0.1) (Buchhorn et al. 2020) to account for open land cover types that would suffer small or no habitat loss impact (Table 1).

Table 1. Land Use Reclassification of the Land Cover Data from the Copernicus Global Land Service (Source: Buchhorn et al. 2020)

Land Cover Class (Copernicus Global Land Service)	Reclassified Land Cover Class
0: No data	0 No habitat loss impact
30: Herbaceous vegetation	
40: Cropland	
50: Build-up	
60: Bare / sparse vegetation	
70: Snow and ice	
80: Permanent water bodies	
90: Herbaceous wetland	
100: Moss and lichen	
200: Open sea	
20: Shrubs	1 Habitat loss impact
111: Closed forest, evergreen needle leaf	
112: Closed forest, evergreen, broad leaf	
113: Closed forest, deciduous needle leaf	
114: Closed forest, deciduous broad leaf	
115: Closed forest, mixed	
116: Closed forest, unknown	
121: Open forest, evergreen needle leaf	
122: Open forest, evergreen broad leaf	
123: Open forest, deciduous needle leaf	
124: Open forest, deciduous broad leaf	
125: Open forest, mixed	
126: Open forest, unknown	

Although the land cover class “Shrubs” may not be highly affected as forests, we assume the construction of powerlines (i.e., distribution lines) could impact shrubland habitats. The raster dataset did not include areas above latitude 78.25°N (Buchhorn et al. 2021). However, these areas mostly do not contain forested habitats. The subset of powerlines within closed or woody habitats was buffered to account for the width of the ROW: 22.5 m for transmission lines and 18 m for distribution lines, based on the World Bank Group Environmental, Health, and Safety (EHS) Guidelines (IFC 2007). We then assigned the ROWs spatially to each ecoregion and calculated their area sizes in m^2. The mapping and geodata calculations were conducted in ArcGISPro 2.9.0 (ESRI [Environmental Systems Research Institute]). The LCA analysis was executed in R 4.2.0 (R Core Team, 2022) with RStudio (version 2022.02.3).

Electricity Production and Consumption Data

Global production and consumption data of electricity from 2019 were obtained from IEA (2021) to match the land cover raster from the same year. The energy data were in terajoules units. We converted them to kWh units by multiplying the values by 2.78 x 10^{-5} to make it compatible with LCA applications, which use kWh for electricity production and consumption.

RESULTS

We calculated 2,628 characterization factors for ecoregions and 1,084 regional and global on a country scale (Appendix B). The characterization factors indicate the potential fraction of species that disappears per m_2 of constructed ROW of powerlines. Out of the 825 ecoregions, we did not calculate PDFs for 133 ecoregions, as they did not have powerlines infrastructure. Within the remaining ecoregions, 629 were affected by transmission lines and 685 by distribution lines. We calculated regional and global characterization factors for 138 countries, excluding the countries which did not have electricity or powerline data.

Regional Characterization Factors on an Ecoregion Level

The regional characterization factors for mammals ranged across all ecoregions from 1.52 x 10^{-14} to 2.49 x 10^{-10} PDF*y/m_2 for transmission lines and from 1.52 x 10^{-14} to 4.6 x 10^{-10} PDF*y/m^2 for distribution lines. The regional impact of transmission lines for birds varied from 1.58 x 10^{-14} to 2.46 x 10^{-10} PDF*y/m^2 and 1.58 x 10^{-14} to 4.48 x 10^{-10} PDF*y/m^2 for distribution lines. Unsurprisingly, large non-forest ecoregions were hardly affected by powerlines. These include tundra, desert, or steppe ecoregions, but also small remote islands without native species (i.e., mammals) populations or powerline infrastructure. Transmission and distribution lines greatly impacted forested ecoregions (Figure 1), especially along coastal areas with high population densities in Central America and Southeast Asia. Maps for birds can be found in Appendix A.

Regional Characterization Factors on a Country Level

The regional characterization factors were aggregated from ecoregions to a country level. The characterization factors for mammals varied from 3.29 x 10^{-19} to 1.3 x 10^{-13} PDF*y/kWh for transmission lines and 1.94 x 10^{-19} to 4.98 x 10^{-13} PDF*y/kWh for distribution lines. The impact on birds ranged from 3.18 x 10^{-19} to 1.29 x 10^{-13} PDF*y/kWh for transmission lines and 1.86 x 10^{-19} to 4.96 x 10^{-13} PDF*y/kWh for transmission lines. Regional characterization factors varied by seven orders of magnitude for transmission and distribution lines across all countries. Most countries within the Middle East had very small characterization factors values. Transmission lines had a high impact in Central America (e.g., Jamaica and Cuba), Southern Sub-Sahara (e.g., Namibia and Equatorial Guinea), Southern and Southeast Europe (e.g., Montenegro and Albania), and Southeast Asia (e.g., Sri Lanka and Nepal). The impacts of distribution lines had similar patterns yet higher effects, especially in Central America (e.g., Haiti and Jamaica), Northeast South America

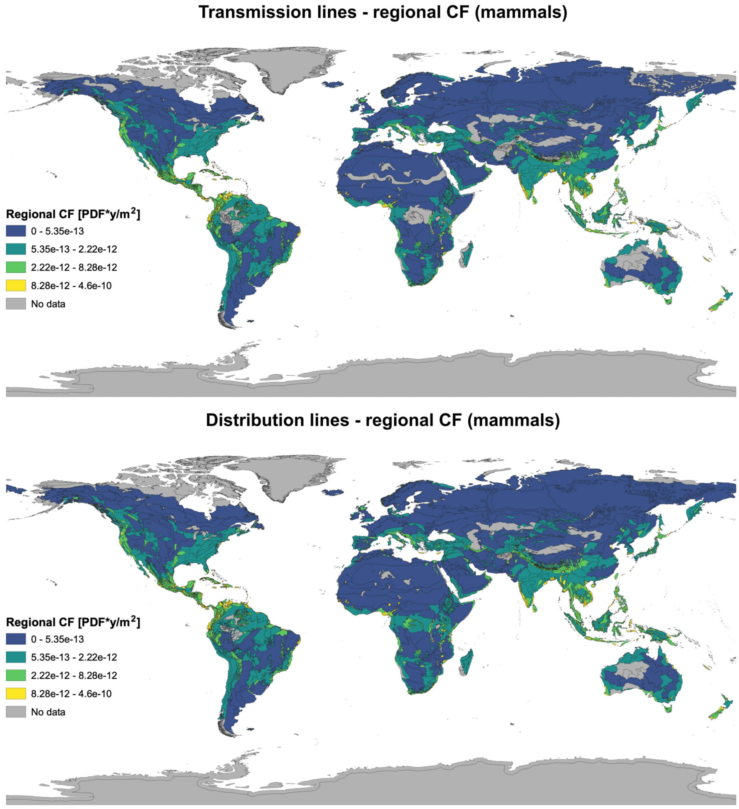

Figure 1. Regional characterization factors of transmission (top) and distribution lines (bottom). Grey areas represent "No data," indicating that no powerlines or mammal species data were available.

(e.g., Guatemala), Southern Sub-Sahara (e.g., Cameroon), and Southeast Asia (e.g., Sri Lanka) (Figure 2). It is important to note that the regional characterization factors derive from the ecoregions and species within each country. Therefore, it is not comparable across countries. Maps for birds can be found in Appendix A.

Global Characterization Factors on a Country Level

While the regional characterization factors represent the potential fraction of species loss per ecoregion, the global characterization factors account for global extinction and hence irreversible extinction. Normally, a global characterization factor represents global species loss within ecoregions. However, we aggregated the regional values to a country level. The global characterization factors of mammals ranged from 2.56×10^{-24} to 4.68×10^{-16} PDF*y/kWh for transmission lines and 6.65×10^{-26} to 2.2×10^{-15} PDF*y/kWh for distribution lines. The variation of the global characterization factors of birds was between 2.47×10^{-24} to 4.7×10^{-16} PDF*y/kWh for transmission lines and 6.42×10^{-26} to 2.19×10^{-15} PDF*y/kWh for distribution lines. The global characterization factors ranged by nine to twelve orders of magnitude for

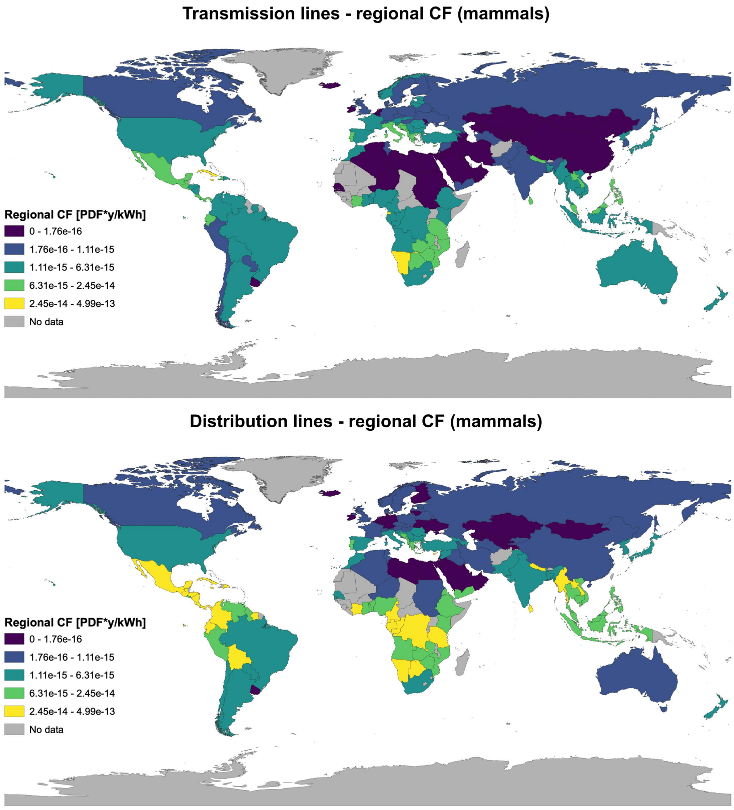

Figure 2. Regional characterization factors of transmission lines (top) and distribution lines (bottom) per country. Grey areas represent "No data," indicating that no electricity or powerlines data were available.

transmission and distribution lines (retrospectively). Transmission and distribution lines greatly impact species richness in Mexico, Jamaica, Indonesia, Sri Lanka, and Ecuador (Figure 3). High global characterization factors from distribution lines also occur in Southern Sub-Saharan countries (e.g., the Democratic Republic of the Congo and Cameroon), Central and South America (e.g., Colombia), and Southeast Asia (e.g., the Philippines). Many of the Middle East countries, as well as northern Europe, had a somewhat small global biodiversity impact from powerlines (e.g., in Qatar, Bahrain, and Iceland). Maps for birds can be found in Appendix A.

DISCUSSION

In this study, we introduced a new methodology to quantify the habitat loss impact of powerlines on terrestrial mammals and birds. Our model adopted an existing approach that assesses land use change in LCA (Chaudhary et al. 2015), integrating recommended LCA metrics, such as PDF or models that generate characterization factors on a regional and global scales (Verones et al. 2017).

Our results present a high variability between characterization factors across ecoregions and countries. It strengthens the importance of regionalization within LCA, as the impacts of powerlines affect areas differently. The regional characterization factors differ from the global ones (Figures 2 and 3). Global extinction potential was higher in tropical countries: Central and South America, Sub-Sahara, and Southeast Asia. It corresponds with areas rich in mammal and bird species (Howard et al. 2020). It highlights the importance of sustainable planning to construct future powerlines in these countries to avoid global biodiversity loss. While the regional characterization factors cannot be compared because they refer only to the ecoregions and the number of species in each country, by applying the GEP (Kuipers et al. 2019), the global characterization factors become comparable as they present a potential global extinction loss.

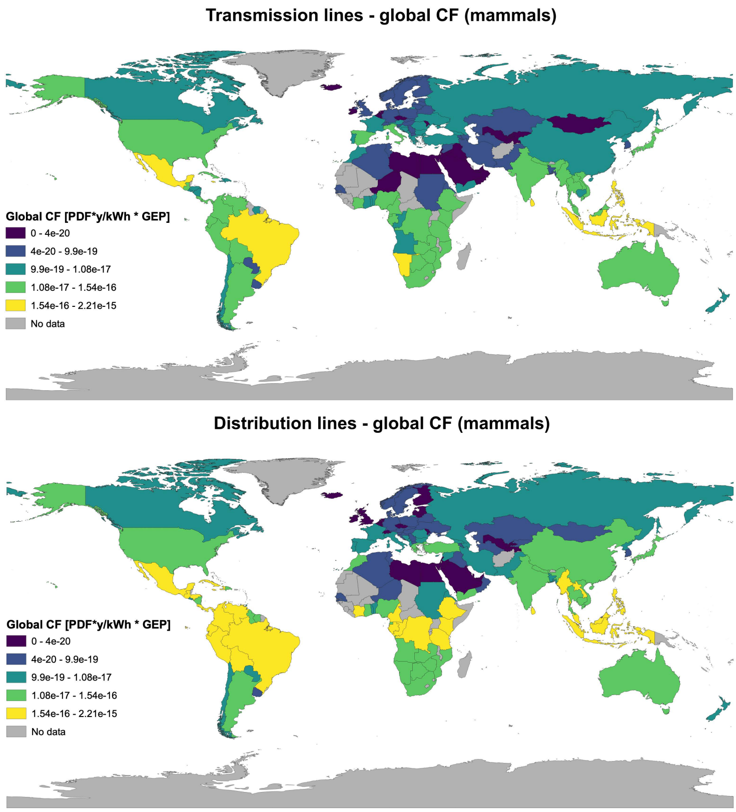

Figure 3. Global CF of transmission (top) and distribution lines (bottom) per country. Grey areas represent "No data," indicating that no electricity or powerlines data were available.

The global grid geodata (Arderne et al. 2020) assembled 3,893,160 km of transmission lines and 5,138,180 km of distribution lines. Our results show that distribution lines have, in most cases, higher impacts on species due to habitat loss. Transmission lines had higher impacts in Australia, Japan, the United States, and Italy. However, distribution lines affected more ecoregions and countries, especially in Indonesia, the Democratic Republic of the Congo, Cameroon, and Mexico. That is presumably because of their extensive network, but perhaps also due to their role in linking transmission lines to rural areas. Yet transmission lines receive the most attention from the scientific community. For instance, Biasotto and Kindel (2018) and Richardson et al. (2017) reviewed only the impacts of transmission lines on biodiversity, while Bernardino et al. (2018) showed that most studies related to bird collisions are focused on high-voltage lines, even though birds may also collide with distribution lines.

In addition, although habitat loss is one of the main drivers of global biodiversity loss (IPBES 2019), it is rarely discussed in the scientific literature (Biasotto and Kindel 2018) as most of the focus is dedicated to the collision and electrocution of birds by powerlines (Richardson et al. 2017; Biasotto and Kindel 2018).

The impact of powerlines occurs on the ecoregion level, where habitat is converted into ROW to accommodate powerlines. Our findings are consistent with those of Chaudhary et al. (2015), who quantified regional species loss caused by land use. Although smaller, our regional characterization factors on the ecoregion level vary only in one or two orders of magnitude (Tables 2 and 3). Similarly, birds had slightly higher values compared to mammals.

The foundation of our model lies in the global grid network data. Although the predictive mapping models reach 75% accuracy rates, they have their share of uncertainties. The transmission lines data, for instance, are derived from OpenStreetMap (Arderne et al. 2020), whose data are created by its community and are not necessarily systematically validated. Furthermore, we can expect an overestimation in the prediction of the grid network in cities and an underestimation in rural areas, as it is based on the grid network topology and the presence of roads. Regardless of its limitations, the global grid dataset is, as Arderne et al. (2020) claim, a "valuable starting point" to assess the global impacts of powerlines on biodiversity.

Another source of uncertainty is the width of the ROWs. The EHS Guidelines describe a large variation among widths for transmission lines between 15 m and 100 m. We used the recommended width provided by the EHS Guidelines as a common international standard (IFC 2007). Our results may be somewhat limited and underestimate habitat loss impacts, especially in countries with many transmission lines crossing forested areas.

Furthermore, it is also important to bear in mind our decision to include bushland as an affected habitat for constructing powerlines. While tall trees must be removed from a ROW, bushes might remain to grow underneath the powerlines. That explains, for instance, why our model predicted high impacts for Namibia, a country rich in savanna and woodland ecoregions. Therefore, highly impacted countries without forested landscapes should be interpreted with caution.

Table 2. Median Values of Regional Characterization Factors for Ecoregions for Land Use Categories from Chaudhary et al. (2015) for Birds and Mammals (Average Assessment)

	Annual crops	Permanent crops	Pasture	Urban	Extensive forestry	Intensive forestry
Birds	4.35×10^{-10}	4.99×10^{-10}	2.99×10^{-10}	7.89×10^{-10}	6.8×10^{-11}	3.21×10^{-10}
Mammals	1.32×10^{-10}	2.57×10^{-11}	8.5×10^{-11}	1.88×10^{-10}	4.25×10^{-11}	3.11×10^{-11}

Table 3. Median Values of Regional Characterization Factors for Ecoregions for ROWs Construction for Mammals and Birds

	Transmission lines	Distribution lines
Birds	2.54×10^{-12}	2.81×10^{-12}
Mammals	2.42×10^{-12}	2.67×10^{-12}

Our study focused on two of the most studied taxonomic groups regarding the impacts of powerlines: birds and mammals (Biasotto and Kindel 2018). However, species composition changes within ROWs can also disturb amphibians, insects, plants, and reptiles (Richardson et al. 2017). Existing IUCN datasets provide distribution data of many taxonomical groups (e.g., amphibians, reptiles, and plants). However, there is a lack of data for species within certain taxonomical groups (i.e., plants), while birds and mammals have very high and recent species coverage data (Cazalis et al. 2022).

Despite its limitations, this study shows that habitat loss due to powerlines affects biodiversity. Our characterization factors can be applied to planning a new powerline construction by quantifying the impact of the new planned routes and selecting the least damaging approach. Alternatively, they can be harmonized into existing LCA models that assess the impacts of the energy sector by accounting also for the distribution of the generated electricity.

It is essential to determine the primary impacts that powerlines pose on biodiversity, as it can be a key to developing mitigation strategies (Richardson et al. 2017). However, our study addressed only the habitat loss pathway of powerlines on biodiversity. What is now needed is a further development of more impact pathways. For example, the collision and electrocution of birds are the most studied impacts of powerlines, yet no study evaluated the cumulative impact of the current grid network on bird populations (Bernardino et al. 2018). In addition, an existing method (Kuipers et al. 2021) can be integrated into our model to quantify potential fragmentation impacts. Adding more impact pathways to LCA will enhance the quality of the impact assessment models, providing a more comprehensive evaluation of the effects of electricity systems.

CONCLUSIONS

The framework of LCA is a common, widespread methodology to assess the environmental impacts of products or services across their entire life cycle. Although some impact pathways on biodiversity are integrated into LCA, they fail to cover all known biodiversity loss drivers (Winter et al. 2017). The development of the global grid network is an essential step in ensuring access to sustainable energy (SDG 7). However, expanding transmission and distribution lines will increase the pressure on terrestrial biodiversity, harming terrestrial ecosystems and biodiversity (SDG 15). Life cycle assessment can play a key role in identifying these trade-offs and assist policymakers in mitigating them. Existing LCA models assess the impacts of electricity production on biodiversity, like hydropower (Dorber et al. 2018, 2019, 2020) and wind power (May et al. 2020, 2021), and our model complements these with an additional perspective on electricity distribution, thereby promoting a holistic approach to quantifying the impacts of energy systems worldwide. Harmonizing and integrating these models in environmental planning can contribute to the sustainable development of renewable energy technologies.

ACKNOWLEDGEMENTS

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REFERENCES

Zorn, C., C. Nicolas, and E.E. Koks. 2020. “Predictive mapping of the global power system using open data.” Scientific Data 7(1):1–12.

Bartzke, G., R. May, K. Bevanger, S. Stokke, and E. Roskaft. 2014. “The effects of powerlines on ungulates and implications for powerline routing and rights-of-way management.” International Journal of Biodiversity and Conservation 6(9):647–662.

Bernardino, J., K. Bevanger, R. Barrientos, J.F. Dwyer, A.T. Marques, R.C. Martins, J.M. Shaw, J.P. Silva, and F. Moreira. 2018. “Bird collisions with powerlines: State of the art and priority areas for research.” Biological Conservation 222:1–13.

Biasotto, L.D., and A. Kindel. 2018. “Powerlines and impacts on biodiversity: A systematic review.” Environmental Impact Assessment Review 71:110–119.

BirdLife International and Handbook of the Birds of the World. 2020. Bird species distribution maps of the world, Version 2020.1. Available at http://datazone.birdlife.org/species/requestdis.

Buchhorn, M., B. Smets, L. Bertels, B. De Roo, M. Lesiv, N. Tsendbazar, L. Li, and A. Tarko. 2021. “Copernicus Global Land Service: Land Cover 100m: version 3 Globe 2015-2019: Product User Manual.” Zenodo 3(4).

Buchhorn, M., B. Smets, L. Bertels, B. De Roo, M. Lesiv, N. Tsendbazar, M. Herold, and S. Fritz. 2020. “Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2019: Globe (V3.0.1).” Zenodo.

Cazalis, V., M. di Marco, S.H.M. Butchart, H.R. Akçakaya, M. González-Suárez, C. Meyer, V. Clausnitzer, M. Böhm, A. Zizka, P. Cardoso, A.M. Schipper, S.P. Bachman, B.E. Young, M. Hoffmann, A. Benítez-López, P.M. Lucas, N. Pettorelli, G. Patoine, M. Pacifici, … and L. Santini. 2022. “Bridging the research-implementation gap in IUCN Red List assessments.” Trends in Ecology and Evolution 37(4):359–370.

Chaudhary, A., F. Verones, L. de Baan, and S. Hellweg. 2015. “Quantifying Land Use Impacts on Biodiversity: Combining Species-Area Models and Vulnerability Indicators.” Environmental Science and Technology 49(16):9987–9995.

Conor, E.F., and E.D. McCoy. 2013. Species-Area Relationships. Encyclopedia of Biodiversity: Second Edition 6:640–650.

de Baan, L., M. Curran, C. Rondinini, P. Visconti, S. Hellweg, and T. Koellner. 2015. “High-resolution assessment of land use impacts on biodiversity in life cycle assessment using species habitat suitability models.” Environmental Science and Technology 49(4):2237–2244.

de Baan, L., C.L. Mutel, M. Curran, S. Hellweg, and T. Koellner. 2013. “Land use in life cycle assessment: Global characterization factors based on regional and global potential species extinction.” Environmental Science and Technology 47(16):9281–9290.

Dorber, M., K. Kuipers, and F. Verones. 2020. “Global characterization factors for terrestrial biodiversity impacts of future land inundation in Life Cycle Assessment.” Science of the Total Environment 712, 134582:1–10.

Dorber, M., K.R. Mattson, O.T. Sandlund, R. May, and F. Verones. 2019. “Quantifying net water consumption of Norwegian hydropower reservoirs and related aquatic biodiversity impacts in Life Cycle Assessment.” Environmental Impact Assessment Review 76(7491):36–46.

Dorber, M., R. May, and F. Verones. 2018. “Modeling Net Land Occupation of Hydropower Reservoirs in Norway for Use in Life Cycle Assessment.” Environmental Science and Technology 52(4):2375–2384.

Drakare, S., J.J. Lennon, and H. Hillebrand. 2006. “The imprint of the geographical, evolutionary and ecological context on species-area relationships.” Ecology Letters 9(2):215–227.

ESRI. (2021). ArcGIS Pro 2.9.0.

Gargiulo, A., P. Girardi, and A. Temporelli. 2017. “LCA of electricity networks: a review.” International Journal of Life Cycle Assessment 22(10):1502–1513.

Gracey, E.O., and F. Verones. 2016. “Impacts from hydropower production on biodiversity in an LCA framework—review and recommendations.” International Journal of Life Cycle Assessment 21(3):412–428.

Hellweg, S., and L. Milá i Canals. 2014. “Emerging approaches, challenges and opportunities in life cycle assessment.” Science 344(6188):1109–1113.

Howard, C., C.H. Flather, and P.A. Stephens. 2020. “A global assessment of the drivers of threatened terrestrial species richness.” Nature Communications 11(1):1–10.

IEA. 2021. World Energy Outlook 2021. International Energy Agency (IEA), Paris, France.

IFC. 2007. General EHS Guidelines: electric power transmission and distribution. International Finance Corporation (IFC.) World Bank Group.

IPBES. 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

IPCC. 2022. Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Shukla, P.R., J. Skea, R. Slade, A. al Khourdajie, R. van Diemen, M. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley. Cambridge, UK: Cambridge University Press, and New York, NY, USA.

ISO 14044. 2006. Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006).

IUCN. 2019. IUCN Red List of Threatened Species. January 2019 (version 6.2). Available at https://www.iucnredlist.org.

Kuipers, K., S. Hellweg, and F. Verones. 2019. “Potential Consequences of Regional Species Loss for Global Species Richness: A Quantitative Approach for Estimating Global Extinction Probabilities.” Environmental Science and Technology 53(9):4728–4738.

Kuipers, K., R. May, and F. Verones. 2021. “Considering habitat conversion and fragmentation in characterization factors for land-use impacts on vertebrate species richness.” Science of the Total Environment 801(89), 149737:1–10.

Latham, A.D.M., and S. Boutin. 2015. "Impacts of Utility and Other Industrial Linear Corridors on Wildlife." Handbook of Road Ecology, pp. 228–236. John Wiley & Sons.

May, R., C.R. Jackson, H. Middel, B.G. Stokke, and F. Verones. 2021. "Life-cycle impacts of wind energy development on bird diversity in Norway." Environmental Impact Assessment Review 90, 106635:1–11.

May, R., H. Middel, B.G. Stokke, C. Jackson, and F. Verones. 2020. "Global life-cycle impacts of onshore wind-power plants on bird richness." Environmental and Sustainability Indicators 8, 100080:1–9.

Olson, D.M., E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, J.A. D'Amico, I. Itoua, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, T.H. Ricketts, Y. Kura, J.F. Lamoreux, W.W. Wettengel, P. Hedao, and K.R. Kassem. 2001. "Terrestrial ecoregions of the world: A new map of life on Earth." BioScience 51(11):933–938.

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Available at https://www.R-project.org.

Richardson, M.L., B.A. Wilson, D.A.S. Aiuto, J.E. Crosby, A. Alonso, F. Dallmeier, and G.K. Golinski. 2017. "A review of the impact of pipelines and powerlines on biodiversity and strategies for mitigation." Biodiversity and Conservation 26(8):1801–1815.

UN. 2021. The Sustainable Development Goals Report.

Verones, F., K. Kuipers, M. Núñez, F. Rosa, L. Scherer, A. Marques, O. Michelsen, V. Barbarossa, B. Jaffe, S. Pfister, and M. Dorber. 2022. "Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment." Ecological Indicators 142, 109204:1–10.

Verones, F., J. Bare, C. Bulle, R. Frischknecht, M. Hauschild, S. Hellweg, A. Henderson, O. Jolliet, A. Laurent, X. Liao, J.P. Lindner, D. Maia de Souza, O. Michelsen, L. Patouillard, S. Pfister, L. Posthuma, V. Prado, B. Ridoutt, R.K. Rosenbaum, … and P. Fantke. 2017. "LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative." Journal of Cleaner Production 161:957–967.

Winter, L., A. Lehmann, N. Finogenova, and M. Finkbeiner. 2017. "Including biodiversity in life cycle assessment – State of the art, gaps and research needs." Environmental Impact Assessment Review 67:88–100.

World Wildlife Fund Terrestrial Ecoregions of the World. Available at https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world.

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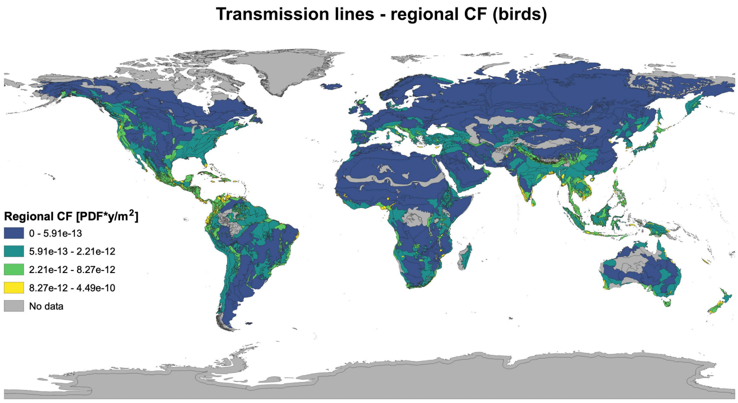
APPENDIX A – FIGURES OF REGIONAL AND GLOBAL CHARACTERIZATION FACTORS FOR BIRDS



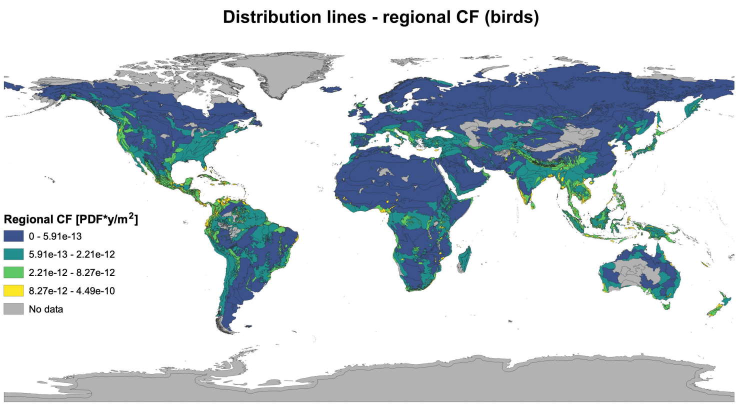


Figure A1. Regional characterization factors of transmission (top) and distribution lines (bottom). Grey areas represent "No data," indicating that no powerlines or bird species data were available.

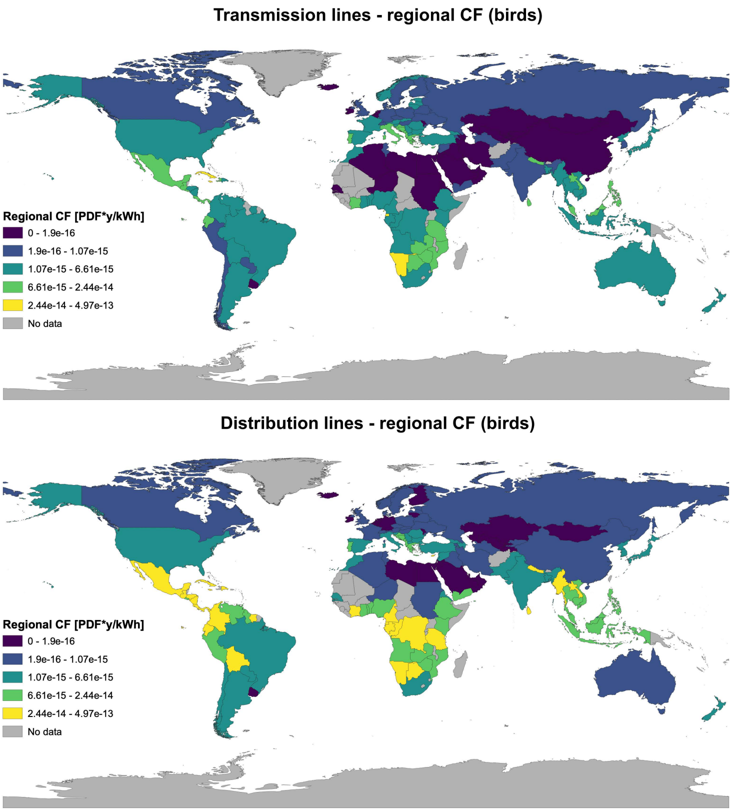
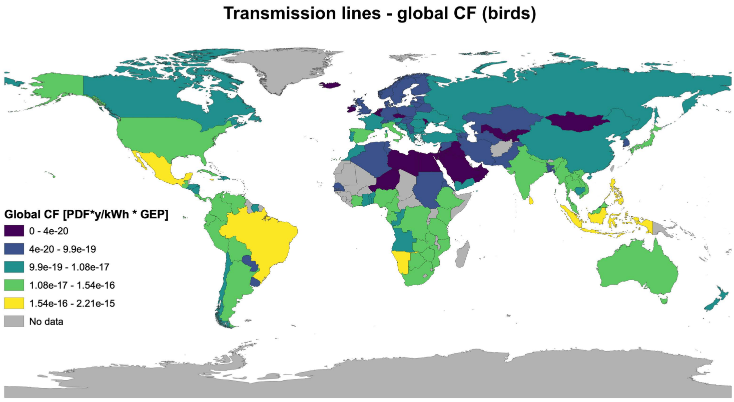


Figure A2. Regional characterization factors of transmission lines (top) and distribution lines (bottom) per country. Grey areas represent "No data," indicating that no electricity or powerlines data were available.



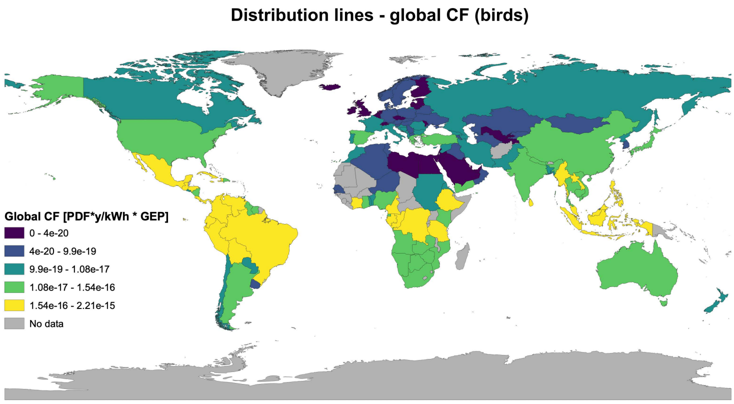


Figure A3. Global characterization factors of transmission (top) and distribution lines (bottom) per country. Grey areas represent "No data," indicating that no electricity or powerlines data were available.

APPENDIX B – REGIONAL AND GLOBAL CHARACTERIZATION FACTORS

Table B1. List of WWF Terrestrial Ecoregions with Regional Characterization Factors (CF) for Habitat Loss Due to Transmission and Distribution Lines

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2]		No. of birds	Birds Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
AA0101	23	-	-	118	-	-
AA0102	36	-	3.38543E-11	251	-	3.34894E-11
AA0103	32	-	-	132	-	-
AA0104	25	-	2.99489E-11	194	-	2.96111E-11
AA0105	184	1.49351E-12	1.49381E-12	537	1.49237E-12	1.49267E-12
AA0106	49	-	9.64465E-12	247	-	9.60958E-12
AA0107	99	1.55031E-11	1.55066E-11	428	1.54902E-11	1.54937E-11
AA0108	45	-	-	214	-	-
AA0109	1	-	-	85	-	-
AA0110	26	-	-	185	-	-
AA0111	57	-	7.33056E-12	271	-	7.31323E-12
AA0112	52	-	-	201	-	-
AA0113	9	1.54313E-11	1.54345E-11	135	1.52960E-11	1.52991E-11
AA0114	1	-	-	52	-	-
AA0115	132	1.90748E-12	1.90769E-12	485	1.90568E-12	1.90589E-12
AA0116	88	1.10980E-11	1.10990E-11	425	1.10884E-11	1.10894E-11
AA0117	106	9.30589E-12	9.30543E-12	419	9.07581E-12	9.07537E-12
AA0118	50	1.33419E-11	1.33461E-11	224	1.32611E-11	1.32653E-11
AA0119	48	-	-	255	-	-
AA0120	153	-	3.26859E-12	531	-	3.26520E-12
AA0121	136	2.55431E-12	2.55433E-12	480	2.54924E-12	2.54926E-12
AA0122	147	2.08089E-12	2.08093E-12	494	2.07882E-12	2.07886E-12
AA0123	141	2.22142E-12	2.22204E-12	397	2.21375E-12	2.21436E-12
AA0124	143	3.41170E-12	3.41230E-12	303	3.38584E-12	3.38642E-12
AA0125	42	-	-	175	-	-
AA0126	15	-	-	125	-	-
AA0127	67	-	-	418	-	-
AA0128	95	-	3.33745E-12	483	-	3.33497E-12
AA0201	63	6.42316E-12	6.42545E-12	307	6.34328E-12	6.34551E-12
AA0202	6	5.07646E-11	5.07811E-11	125	5.03105E-11	5.03267E-11
AA0203	21	-	2.33802E-11	208	-	2.29318E-11
AA0204	43	7.53146E-12	7.53469E-12	263	7.41348E-12	7.41661E-12
AA0401	0	-	-	80	-	-
AA0402	93	1.14639E-12	1.14622E-12	465	1.11744E-12	1.11728E-12
AA0403	2	-	-	121	-	-
AA0404	1	9.89031E-12	9.88983E-12	135	9.15671E-12	9.15630E-12
AA0405	2	1.83498E-12	1.83490E-12	142	1.72309E-12	1.72303E-12
AA0406	2	5.56363E-12	5.56370E-12	150	5.27359E-12	5.27365E-12
AA0407	2	-	-	108	-	-
AA0408	1	1.09494E-11	1.09485E-11	137	1.03037E-11	1.03029E-11
AA0409	72	8.10555E-13	8.10526E-13	436	7.78663E-13	7.78636E-13
AA0410	1	1.05976E-11	1.05979E-11	127	1.00547E-11	1.00550E-11
AA0411	32	7.29913E-12	7.29829E-12	215	7.29993E-12	7.29908E-12
AA0412	32	7.65503E-12	7.65487E-12	231	7.65581E-12	7.65564E-12

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Distribution
AA0413	32	4.35633E-12	4.35591E-12	224	4.36351E-12	4.36310E-12
AA0414	1	2.56974E-11	2.57014E-11	119	2.44070E-11	2.44106E-11
AA0701	65	1.25585E-12	1.25585E-12	296	1.25476E-12	1.25476E-12
AA0702	111	5.09613E-13	5.09583E-13	471	5.09320E-13	5.09290E-13
AA0703	80	1.71360E-12	1.71362E-12	379	1.70975E-12	1.70977E-12
AA0704	93	-	5.27785E-13	382	-	5.31336E-13
AA0705	108	1.47953E-12	1.47942E-12	394	1.47453E-12	1.47443E-12
AA0706	80	5.46608E-13	5.46611E-13	339	5.51942E-13	5.51945E-13
AA0707	91	3.90244E-13	3.90242E-13	330	3.93567E-13	3.93566E-13
AA0708	62	-	-	341	-	-
AA0709	58	-	8.29092E-13	272	-	8.37813E-13
AA0801	1	2.44623E-12	2.44620E-12	130	2.32405E-12	2.32403E-12
AA0802	48	6.34800E-13	6.34799E-13	279	6.43031E-13	6.43030E-13
AA0803	72	4.67946E-13	4.67942E-13	356	4.67336E-13	4.67331E-13
AA1001	46	1.13299E-11	1.13287E-11	286	1.12442E-11	1.12431E-11
AA1002	149	-	1.64967E-11	410	-	1.64850E-11
AA1003	2	3.37928E-12	3.37926E-12	78	3.29603E-12	3.29601E-12
AA1101	0	-	-	98	-	-
AA1201	34	1.09210E-12	1.09212E-12	252	1.10512E-12	1.10514E-12
AA1202	40	-	-	284	-	-
AA1203	39	2.36748E-12	2.36745E-12	327	2.37689E-12	2.37686E-12
AA1204	25	1.37090E-11	1.37094E-11	251	1.35413E-11	1.35417E-11
AA1205	31	1.00645E-11	1.00639E-11	283	9.94584E-12	9.94526E-12
AA1206	38	5.98243E-12	5.98220E-12	342	5.96852E-12	5.96829E-12
AA1207	62	7.23811E-13	7.23796E-13	333	7.22566E-13	7.22552E-13
AA1208	49	4.90218E-12	4.90215E-12	353	4.84950E-12	4.84947E-12
AA1209	48	9.28876E-13	9.28879E-13	291	9.28925E-13	9.28927E-13
AA1210	38	3.19750E-12	3.19724E-12	281	3.14856E-12	3.14831E-12
AA1301	50	-	1.81113E-12	274	-	1.91162E-12
AA1302	42	-	-	207	-	-
AA1303	30	-	-	149	-	-
AA1304	64	-	-	278	-	-
AA1305	45	3.51147E-13	-	234	3.78846E-13	-
AA1306	31	-	-	221	-	-
AA1307	52	9.26033E-13	9.26033E-13	246	9.94605E-13	9.94606E-13
AA1308	55	2.65172E-13	-	276	2.84710E-13	-
AA1309	56	3.95658E-13	3.95657E-13	343	4.10501E-13	4.10500E-13
AA1310	57	3.35416E-13	3.35417E-13	231	3.61692E-13	3.61693E-13
AA1401	122	9.56404E-12	9.56421E-12	510	9.54680E-12	9.54697E-12
AN1101	0	-	-	33	-	-
AN1102	0	-	-	27	-	-
AN1103	0	-	-	53	-	-
AN1104	0	-	-	50	-	-
AT0101	343	3.25139E-12	3.25197E-12	1013	3.09402E-12	3.09455E-12
AT0102	209	1.81351E-12	1.81377E-12	639	1.72550E-12	1.72574E-12

Ecoregion code	No. of mammals	Mammals		No. of birds	Birds	
		Regional CF [PDF*y/m2]			Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
AT0103	236	8.84720E-12	8.84883E-12	772	8.38391E-12	8.38537E-12
AT0104	173	-	8.30056E-13	485	-	7.85481E-13
AT0105	10	-	1.19961E-10	94	-	1.18719E-10
AT0106	120	1.64963E-11	1.65016E-11	466	1.56469E-11	1.56516E-11
AT0107	219	6.55282E-12	6.55454E-12	680	6.28221E-12	6.28379E-12
AT0108	319	5.00500E-12	5.00536E-12	1007	4.61272E-12	4.61302E-12
AT0109	260	1.38037E-11	1.38054E-11	826	1.26078E-11	1.26093E-11
AT0110	187	-	3.71908E-12	490	-	3.54104E-12
AT0111	247	1.78878E-12	1.78941E-12	680	1.67180E-12	1.67234E-12
AT0112	249	1.23363E-12	1.23372E-12	832	1.10567E-12	1.10574E-12
AT0113	3	-	-	61	-	-
AT0114	228	1.06816E-11	1.06839E-11	626	9.98593E-12	9.98794E-12
AT0115	117	5.83306E-11	5.83329E-11	441	6.26264E-11	6.26291E-11
AT0116	147	1.12821E-11	1.12825E-11	570	1.15975E-11	1.15980E-11
AT0117	142	2.05985E-12	2.05986E-12	221	2.04670E-12	2.04671E-12
AT0118	164	1.15513E-12	1.15513E-12	228	1.14900E-12	1.14900E-12
AT0119	139	7.58559E-12	7.58604E-12	540	7.55814E-12	7.55859E-12
AT0120	5	-	-	57	-	-
AT0121	153	-	2.99246E-10	487	-	2.93199E-10
AT0122	103	2.37755E-11	2.37833E-11	392	2.28119E-11	2.28191E-11
AT0123	155	5.00753E-12	5.00825E-12	559	4.69999E-12	4.70062E-12
AT0124	311	-	6.39496E-13	886	-	6.04660E-13
AT0125	283	2.26116E-12	2.26131E-12	831	2.15401E-12	2.15415E-12
AT0126	246	7.90913E-13	7.90985E-13	713	7.44349E-13	7.44412E-13
AT0127	9	2.49854E-10	2.50025E-10	98	2.46226E-10	2.46393E-10
AT0128	168	2.02404E-12	2.02413E-12	619	1.89129E-12	1.89137E-12
AT0129	214	-	2.67827E-12	563	-	2.55163E-12
AT0130	224	1.64855E-12	1.64886E-12	638	1.55247E-12	1.55274E-12
AT0201	2	-	-	64	-	-
AT0202	124	-	1.55680E-12	214	-	1.54625E-12
AT0203	155	7.66750E-12	7.66752E-12	545	7.06834E-12	7.06835E-12
AT0701	233	3.03317E-13	3.03337E-13	805	2.96989E-13	2.97009E-13
AT0702	144	1.37047E-12	1.37048E-12	533	1.33381E-12	1.33381E-12
AT0703	0	-	-	27	-	-
AT0704	348	1.72629E-13	1.72636E-13	1048	1.69710E-13	1.69717E-13
AT0705	355	2.24918E-13	2.24929E-13	1132	2.20715E-13	2.20725E-13
AT0706	264	4.14921E-13	4.14934E-13	788	4.03600E-13	4.03612E-13
AT0707	319	3.06653E-13	3.06707E-13	903	3.03542E-13	3.03595E-13
AT0708	178	2.61984E-11	2.61968E-11	600	2.50899E-11	2.50885E-11
AT0709	178	5.16682E-13	5.16682E-13	551	5.04147E-13	5.04147E-13
AT0710	91	-	2.69860E-11	386	-	2.45228E-11
AT0711	316	6.44428E-13	6.44441E-13	1012	6.26696E-13	6.26708E-13
AT0712	353	2.96104E-13	2.96122E-13	1027	2.92871E-13	2.92889E-13
AT0713	229	6.38552E-14	6.38554E-14	818	6.08252E-14	6.08253E-14
AT0714	192	-	1.14919E-11	673	-	1.10797E-11

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Mammals Regional CF [PDF*y/m2] Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Birds Regional CF [PDF*y/m2] Distribution
AT0715	264	1.95656E-13	1.95659E-13	902	1.89369E-13	1.89372E-13
AT0716	310	9.19386E-13	9.19400E-13	983	8.98133E-13	8.98146E-13
AT0717	199	7.67213E-13	7.67251E-13	615	7.55852E-13	7.55888E-13
AT0718	217	3.67655E-13	3.67683E-13	803	3.63677E-13	3.63704E-13
AT0719	239	4.63873E-13	4.63882E-13	711	4.52776E-13	4.52785E-13
AT0720	0	-	-	22	-	-
AT0721	351	1.27380E-12	1.27402E-12	1075	1.25373E-12	1.25395E-12
AT0722	251	1.23510E-13	1.23520E-13	750	1.20142E-13	1.20152E-13
AT0723	252	5.06964E-13	5.07026E-13	772	5.01031E-13	5.01091E-13
AT0724	148	5.69988E-12	5.69977E-12	537	5.50455E-12	5.50444E-12
AT0725	278	3.88627E-13	3.88629E-13	772	3.80822E-13	3.80824E-13
AT0726	200	7.15158E-13	7.15167E-13	608	6.87373E-13	6.87381E-13
AT0801	35	6.87788E-12	6.87794E-12	178	6.22471E-12	6.22477E-12
AT0802	0	-	-	39	-	-
AT0803	0	-	-	46	-	-
AT0901	184	-	-	596	-	-
AT0902	82	2.41777E-11	2.41793E-11	351	2.32583E-11	2.32597E-11
AT0903	89	-	-	426	-	-
AT0904	95	-	-	489	-	-
AT0905	134	1.13129E-12	1.13131E-12	538	1.05980E-12	1.05982E-12
AT0906	119	9.46433E-12	9.46442E-12	479	9.34755E-12	9.34764E-12
AT0907	297	1.28860E-12	1.28863E-12	878	1.25431E-12	1.25434E-12
AT0908	128	5.63968E-12	5.63956E-12	504	5.65591E-12	5.65579E-12
AT1001	136	7.75736E-12	7.75782E-12	567	7.61482E-12	7.61527E-12
AT1002	158	2.75520E-12	2.75531E-12	682	2.71301E-12	2.71311E-12
AT1003	108	-	-	382	-	-
AT1004	223	7.47904E-13	7.47924E-13	656	7.38433E-13	7.38452E-13
AT1005	254	6.37777E-11	6.37795E-11	815	6.16049E-11	6.16066E-11
AT1006	162	2.37102E-11	2.37164E-11	534	2.30411E-11	2.30470E-11
AT1007	238	8.19007E-13	8.19036E-13	810	7.88145E-13	7.88172E-13
AT1008	192	7.96000E-12	7.96030E-12	699	7.64215E-12	7.64243E-12
AT1009	161	7.74091E-13	7.74093E-13	527	8.05356E-13	8.05357E-13
AT1010	112	1.52875E-11	1.52876E-11	472	1.47043E-11	1.47044E-11
AT1011	84	-	-	162	-	-
AT1012	150	7.15949E-12	7.15929E-12	557	7.35098E-12	7.35077E-12
AT1013	232	-	7.91382E-11	771	-	7.79472E-11
AT1014	146	1.90486E-11	1.90484E-11	537	1.84927E-11	1.84926E-11
AT1015	208	6.06883E-12	6.06979E-12	675	5.89629E-12	5.89719E-12
AT1201	116	7.68390E-12	7.68369E-12	448	8.02596E-12	8.02573E-12
AT1202	106	4.02772E-12	4.02763E-12	427	4.18225E-12	4.18215E-12
AT1203	121	2.99355E-12	2.99356E-12	435	3.02238E-12	3.02240E-12
AT1301	5	-	-	52	-	-
AT1302	60	2.29533E-12	2.29535E-12	262	2.13834E-12	2.13835E-12
AT1303	63	-	-	348	-	-
AT1304	48	-	-	253	-	-

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2]		No. of birds	Birds Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
AT1305	117	1.27267E-12	1.27268E-12	615	1.22019E-12	1.22019E-12
AT1306	36	2.79897E-12	2.79898E-12	251	2.65477E-12	2.65479E-12
AT1307	78	-	-	370	-	-
AT1308	0	-	-	22	-	-
AT1309	143	2.74021E-13	2.74030E-13	464	2.68061E-13	2.68069E-13
AT1310	113	4.11068E-12	4.11076E-12	413	3.94708E-12	3.94716E-12
AT1311	81	-	-	216	-	-
AT1312	57	-	-	197	-	-
AT1313	194	-	2.06820E-12	670	-	1.97362E-12
AT1314	158	4.13151E-13	4.13151E-13	464	4.11288E-13	4.11288E-13
AT1315	86	-	-	309	-	-
AT1316	148	7.89572E-13	7.89569E-13	501	7.54916E-13	7.54913E-13
AT1318	6	-	-	90	-	-
AT1319	71	-	3.14329E-12	372	-	3.02527E-12
AT1320	64	6.91402E-13	6.91430E-13	271	6.29005E-13	6.29028E-13
AT1321	59	2.17766E-12	2.17776E-12	217	1.89247E-12	1.89254E-12
AT1322	124	1.41751E-12	1.41751E-12	401	1.41663E-12	1.41662E-12
AT1401	246	1.10568E-11	1.10581E-11	745	1.04795E-11	1.04807E-11
AT1402	225	1.93025E-11	1.93042E-11	695	1.76094E-11	1.76109E-11
AT1403	212	1.40773E-11	1.40787E-11	705	1.30882E-11	1.30893E-11
AT1404	64	-	-	192	-	-
AT1405	124	2.15498E-10	2.15529E-10	537	2.17478E-10	2.17510E-10
IM0101	15	-	-	159	-	-
IM0102	229	6.04942E-13	6.05128E-13	556	6.03868E-13	6.04053E-13
IM0103	203	2.23723E-12	2.23753E-12	497	2.23341E-12	2.23371E-12
IM0104	185	3.83410E-12	3.83553E-12	476	3.82486E-12	3.82628E-12
IM0105	161	4.60681E-12	4.60728E-12	742	4.66369E-12	4.66418E-12
IM0106	138	7.31092E-12	7.31245E-12	480	7.19226E-12	7.19374E-12
IM0107	158	8.16314E-12	8.16320E-12	482	7.94299E-12	7.94305E-12
IM0108	168	1.57915E-11	1.57930E-11	605	1.56505E-11	1.56520E-11
IM0109	128	-	9.52580E-12	653	-	9.67936E-12
IM0110	0	-	-	49	-	-
IM0111	95	7.49519E-13	7.49567E-13	490	8.13308E-13	8.13364E-13
IM0112	105	1.59785E-11	1.59869E-11	385	1.59054E-11	1.59138E-11
IM0113	114	4.72239E-12	4.72314E-12	406	4.70482E-12	4.70558E-12
IM0114	54	7.14266E-12	7.14364E-12	314	7.08532E-12	7.08629E-12
IM0115	194	6.40155E-12	6.40218E-12	831	6.77140E-12	6.77211E-12
IM0116	65	1.94217E-11	1.94216E-11	396	1.95361E-11	1.95360E-11
IM0117	187	2.12076E-12	2.12085E-12	782	2.09836E-12	2.09844E-12
IM0118	158	4.07228E-13	4.07323E-13	595	4.02462E-13	4.02555E-13
IM0119	206	2.56472E-12	2.56499E-12	729	2.52033E-12	2.52059E-12
IM0120	177	1.04890E-12	1.04896E-12	736	1.05663E-12	1.05669E-12
IM0121	191	4.25718E-12	4.25748E-12	614	4.21307E-12	4.21336E-12
IM0122	72	2.87066E-11	2.87092E-11	342	2.83687E-11	2.83712E-11
IM0123	98	2.51759E-12	2.51778E-12	375	2.49468E-12	2.49486E-12

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Mammals Regional CF [PDF*y/m2] Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Birds Regional CF [PDF*y/m2] Distribution
IM0124	105	8.42456E-12	8.42482E-12	485	8.54774E-12	8.54801E-12
IM0125	11	-	4.60044E-10	274	-	4.48868E-10
IM0126	141	6.38575E-12	6.38801E-12	666	6.44720E-12	6.44950E-12
IM0127	50	-	-	188	-	-
IM0128	76	1.39906E-11	1.39926E-11	321	1.39139E-11	1.39159E-11
IM0129	91	2.40890E-12	2.40946E-12	369	2.39886E-12	2.39941E-12
IM0130	51	2.43187E-11	2.43244E-11	281	2.40269E-11	2.40325E-11
IM0131	212	2.06834E-12	2.06885E-12	824	2.05414E-12	2.05464E-12
IM0132	176	4.63449E-12	4.63512E-12	728	4.59643E-12	4.59705E-12
IM0133	15	-	-	122	-	-
IM0134	104	5.86701E-12	5.86681E-12	496	6.04289E-12	6.04268E-12
IM0135	101	9.38905E-12	9.38851E-12	471	9.62603E-12	9.62546E-12
IM0136	201	6.55570E-12	6.55605E-12	605	6.44957E-12	6.44991E-12
IM0137	320	6.67636E-13	6.67760E-13	923	6.56393E-13	6.56513E-13
IM0138	163	1.82618E-11	1.82631E-11	511	1.80261E-11	1.80274E-11
IM0139	177	7.24413E-12	7.24482E-12	630	7.17774E-12	7.17842E-12
IM0140	207	-	5.03037E-12	723	-	4.99599E-12
IM0141	184	1.36165E-11	1.36154E-11	612	1.33941E-11	1.33931E-11
IM0142	62	1.12537E-11	1.12543E-11	394	1.26201E-11	1.26208E-11
IM0143	59	-	1.75279E-11	268	-	1.73512E-11
IM0144	205	1.99161E-11	1.99154E-11	542	1.97937E-11	1.97930E-11
IM0145	160	9.48157E-11	9.48114E-11	466	9.38942E-11	9.38900E-11
IM0146	223	2.73138E-12	2.73187E-12	588	2.71433E-12	2.71482E-12
IM0147	129	2.75985E-11	2.75995E-11	494	2.70598E-11	2.70608E-11
IM0148	0	-	-	143	-	-
IM0149	202	1.29960E-12	1.29964E-12	811	1.27400E-12	1.27404E-12
IM0150	111	1.27994E-11	1.27998E-11	446	1.30386E-11	1.30390E-11
IM0151	110	1.33930E-11	1.33966E-11	443	1.36747E-11	1.36785E-11
IM0152	191	6.88331E-12	6.88323E-12	602	6.81613E-12	6.81604E-12
IM0153	152	7.03741E-12	7.03954E-12	423	7.02353E-12	7.02565E-12
IM0154	81	1.96570E-11	1.96673E-11	330	2.00302E-11	2.00409E-11
IM0155	79	8.01309E-11	8.01910E-11	298	8.14360E-11	8.14981E-11
IM0156	23	-	1.09881E-10	200	-	1.09034E-10
IM0157	151	1.42999E-11	1.43091E-11	466	1.42748E-11	1.42839E-11
IM0158	197	9.95963E-13	9.96639E-13	583	9.94884E-13	9.95558E-13
IM0159	174	3.54086E-12	3.54219E-12	532	3.53701E-12	3.53833E-12
IM0160	142	2.95687E-12	2.95821E-12	454	2.95159E-12	2.95292E-12
IM0161	184	3.38119E-12	3.38240E-12	503	3.37485E-12	3.37605E-12
IM0162	58	1.69060E-11	1.69083E-11	350	1.83854E-11	1.83881E-11
IM0163	239	3.40377E-12	3.40449E-12	723	3.37781E-12	3.37851E-12
IM0164	97	1.24508E-11	1.24521E-11	443	1.21599E-11	1.21611E-11
IM0165	101	1.10883E-11	1.10885E-11	448	1.08436E-11	1.08438E-11
IM0166	112	8.78528E-13	8.78529E-13	670	9.64220E-13	9.64220E-13
IM0167	125	9.70940E-12	9.71291E-12	407	9.66415E-12	9.66764E-12
IM0168	118	6.12846E-12	6.13025E-12	436	6.10769E-12	6.10947E-12

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2]		No. of birds	Birds Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
IM0169	87	1.47558E-11	1.47614E-11	406	1.46065E-11	1.46120E-11
IM0170	29	4.87772E-11	4.87749E-11	193	4.92078E-11	4.92055E-11
IM0171	52	8.16867E-11	8.16334E-11	309	8.41185E-11	8.40620E-11
IM0172	67	6.29561E-12	6.29262E-12	319	6.35421E-12	6.35116E-12
IM0201	91	1.08652E-12	1.08652E-12	424	1.17685E-12	1.17686E-12
IM0202	233	9.91052E-13	9.91096E-13	749	9.73869E-13	9.73912E-13
IM0203	79	1.84342E-12	1.84342E-12	453	2.14984E-12	2.14984E-12
IM0204	56	1.06282E-11	1.06281E-11	332	1.17840E-11	1.17838E-11
IM0205	151	8.40714E-12	8.40718E-12	641	8.28869E-12	8.28873E-12
IM0206	88	8.38006E-13	8.38006E-13	486	9.58695E-13	9.58694E-13
IM0207	96	1.52275E-12	1.52275E-12	479	1.58983E-12	1.58982E-12
IM0208	69	4.12890E-12	4.12916E-12	392	4.80248E-12	4.80282E-12
IM0209	109	3.65501E-12	3.65496E-12	441	3.72852E-12	3.72847E-12
IM0210	208	2.59440E-12	2.59464E-12	619	2.55756E-12	2.55780E-12
IM0211	173	9.17947E-12	9.17950E-12	575	9.08538E-12	9.08541E-12
IM0212	78	5.06600E-12	5.06910E-12	352	5.15531E-12	5.15852E-12
IM0301	227	2.98525E-12	2.98599E-12	886	3.15456E-12	3.15539E-12
IM0302	64	3.34761E-11	3.34841E-11	331	3.30768E-11	3.30846E-11
IM0303	135	-	2.77301E-11	609	-	2.81867E-11
IM0304	157	9.34473E-11	9.34784E-11	487	9.33569E-11	9.33879E-11
IM0401	229	3.02291E-12	3.02354E-12	859	3.13376E-12	3.13443E-12
IM0402	179	-	2.46994E-11	672	-	2.47424E-11
IM0403	167	3.64879E-12	3.64949E-12	703	4.10886E-12	4.10976E-12
IM0501	217	9.04665E-12	9.04743E-12	766	9.46584E-12	9.46669E-12
IM0502	174	5.08896E-12	5.08937E-12	730	5.73416E-12	5.73468E-12
IM0701	160	4.72442E-12	4.72435E-12	745	4.77664E-12	4.77657E-12
IM0901	61	5.26488E-12	5.26488E-12	381	5.98700E-12	5.98700E-12
IM1001	175	5.91350E-11	5.91430E-11	470	5.90228E-11	5.90308E-11
IM1301	109	5.58710E-13	5.58702E-13	512	5.66733E-13	5.66724E-13
IM1302	46	6.28423E-12	6.28416E-12	287	7.33477E-12	7.33467E-12
IM1303	148	3.16872E-13	3.16871E-13	718	3.30924E-13	3.30923E-13
IM1304	71	6.27083E-13	6.27110E-13	381	6.57007E-13	6.57037E-13
IM1401	68	3.75224E-11	3.75253E-11	380	4.15074E-11	4.15109E-11
IM1402	230	1.22785E-11	1.22809E-11	738	1.20968E-11	1.20991E-11
IM1403	78	3.94110E-11	3.94113E-11	471	4.42914E-11	4.42917E-11
IM1404	219	1.48909E-11	1.48945E-11	733	1.47446E-11	1.47481E-11
IM1405	232	6.90069E-12	6.90396E-12	567	6.88652E-12	6.88977E-12
IM1406	58	1.30775E-11	1.30779E-11	361	1.33115E-11	1.33120E-11
NA0201	118	5.04755E-12	5.04790E-12	429	5.15993E-12	5.16030E-12
NA0301	1	-	-	28	-	-
NA0302	208	1.18357E-12	1.18372E-12	524	1.20905E-12	1.20920E-12
NA0303	198	4.07713E-12	4.07814E-12	577	4.22205E-12	4.22314E-12
NA0401	55	2.11233E-12	2.11247E-12	255	2.17746E-12	2.17761E-12
NA0402	74	9.88405E-13	9.88163E-13	263	1.07455E-12	1.07426E-12
NA0403	71	1.21407E-12	1.21389E-12	270	1.30857E-12	1.30836E-12

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Mammals Regional CF [PDF*y/m2] Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Birds Regional CF [PDF*y/m2] Distribution
NA0404	74	6.08412E-13	6.08322E-13	280	7.06675E-13	7.06553E-13
NA0405	67	3.68886E-12	3.68783E-12	331	4.63454E-12	4.63292E-12
NA0406	55	4.27284E-13	4.27255E-13	279	4.42576E-13	4.42545E-13
NA0407	56	1.36700E-12	1.36691E-12	286	1.42589E-12	1.42579E-12
NA0408	44	3.86036E-12	3.86001E-12	239	4.00375E-12	4.00337E-12
NA0409	57	1.79855E-12	1.79852E-12	308	2.04705E-12	2.04701E-12
NA0410	58	6.65962E-13	6.65932E-13	303	6.86053E-13	6.86021E-13
NA0411	62	1.96646E-12	1.96598E-12	318	2.05212E-12	2.05160E-12
NA0412	61	2.98188E-12	2.98199E-12	262	3.55587E-12	3.55603E-12
NA0413	71	5.95143E-13	5.95106E-13	319	6.48559E-13	6.48515E-13
NA0414	63	7.03337E-13	7.03283E-13	282	7.54478E-13	7.54416E-13
NA0415	64	8.72408E-13	8.72419E-13	293	1.00442E-12	1.00444E-12
NA0416	67	4.81700E-13	4.81678E-13	282	5.47318E-13	5.47289E-13
NA0417	76	1.03193E-11	1.03178E-11	227	1.10213E-11	1.10195E-11
NA0501	58	2.48641E-12	2.48637E-12	234	3.03419E-12	3.03413E-12
NA0502	62	6.69674E-13	6.69651E-13	264	8.83545E-13	8.83506E-13
NA0503	146	1.81412E-12	1.81397E-12	329	2.07199E-12	2.07180E-12
NA0504	41	2.11631E-11	2.11610E-11	297	2.15013E-11	2.14991E-11
NA0505	92	2.20202E-12	2.20199E-12	255	2.56741E-12	2.56738E-12
NA0506	85	7.30743E-13	7.30716E-13	301	9.01731E-13	9.01690E-13
NA0507	87	2.26860E-12	2.26848E-12	266	2.91193E-12	2.91173E-12
NA0508	101	3.11979E-12	3.11946E-12	270	3.68130E-12	3.68085E-12
NA0509	57	1.05090E-12	1.05089E-12	200	1.45748E-12	1.45746E-12
NA0510	87	1.85293E-12	1.85281E-12	279	2.03437E-12	2.03423E-12
NA0511	112	1.27001E-12	1.26999E-12	295	1.50007E-12	1.50004E-12
NA0512	115	2.77560E-12	2.77533E-12	271	3.20969E-12	3.20932E-12
NA0513	41	5.60675E-11	5.60587E-11	277	6.67611E-11	6.67487E-11
NA0514	60	6.56019E-13	6.56015E-13	237	8.50359E-13	8.50352E-13
NA0515	94	3.11533E-11	3.11537E-11	263	3.43543E-11	3.43547E-11
NA0516	92	3.33934E-12	3.33910E-12	276	3.66318E-12	3.66289E-12
NA0517	55	1.48849E-12	1.48843E-12	322	1.66888E-12	1.66880E-12
NA0518	90	4.36481E-13	4.36470E-13	281	5.53568E-13	5.53551E-13
NA0519	80	1.37358E-11	1.37361E-11	305	1.47860E-11	1.47863E-11
NA0520	40	1.10879E-12	1.10881E-12	222	1.52126E-12	1.52130E-12
NA0521	48	2.63102E-12	2.63096E-12	176	3.93679E-12	3.93665E-12
NA0522	81	2.06611E-12	2.06601E-12	251	2.55816E-12	2.55802E-12
NA0523	60	1.38522E-12	1.38506E-12	304	1.67756E-12	1.67733E-12
NA0524	75	5.55267E-12	5.55122E-12	270	6.49936E-12	6.49736E-12
NA0525	6	-	-	128	-	-
NA0526	64	5.78170E-11	5.78154E-11	256	5.98345E-11	5.98327E-11
NA0527	118	3.45189E-12	3.45182E-12	279	3.81958E-12	3.81949E-12
NA0528	109	7.66939E-13	7.66937E-13	293	1.04251E-12	1.04251E-12
NA0529	51	9.34232E-13	9.34115E-13	320	1.05587E-12	1.05572E-12
NA0530	97	4.08651E-12	4.08636E-12	264	4.65591E-12	4.65572E-12
NA0601	29	-	-	170	-	-

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2]		No. of birds	Birds Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
NA0602	47	2.57667E-13	2.57657E-13	223	2.84974E-13	2.84962E-13
NA0603	34	1.52628E-12	1.52629E-12	175	2.56910E-12	2.56912E-12
NA0604	38	2.56654E-12	2.56656E-12	150	3.88595E-12	3.88600E-12
NA0605	48	2.48771E-13	2.48761E-13	246	2.74414E-13	2.74401E-13
NA0606	32	1.21236E-13	1.21235E-13	157	1.36153E-13	1.36152E-13
NA0607	44	7.34330E-14	7.34330E-14	198	1.23269E-13	1.23269E-13
NA0608	60	2.21738E-13	2.21734E-13	260	2.76580E-13	2.76574E-13
NA0609	49	1.69705E-13	1.69703E-13	239	1.94870E-13	1.94867E-13
NA0610	52	2.17575E-13	2.17576E-13	203	2.99964E-13	2.99966E-13
NA0611	9	5.37160E-12	5.37138E-12	161	6.63218E-12	6.63185E-12
NA0612	44	8.92032E-14	8.92031E-14	191	1.16884E-13	1.16884E-13
NA0613	55	2.24475E-13	2.24476E-13	212	3.20022E-13	3.20025E-13
NA0614	51	1.09894E-13	1.09894E-13	196	1.59373E-13	1.59374E-13
NA0615	7	4.33588E-11	4.33617E-11	136	5.84604E-11	5.84655E-11
NA0616	43	2.67140E-13	2.67137E-13	200	2.96638E-13	2.96634E-13
NA0617	47	8.52366E-13	8.52351E-13	164	1.16447E-12	1.16445E-12
NA0701	84	1.90443E-12	1.90419E-12	399	2.00022E-12	1.99995E-12
NA0801	89	2.33456E-12	2.33449E-12	274	2.39615E-12	2.39608E-12
NA0802	80	1.73872E-13	1.73870E-13	312	1.89339E-13	1.89336E-13
NA0803	96	4.11976E-13	4.11955E-13	338	4.67563E-13	4.67536E-13
NA0804	101	2.86760E-13	2.86732E-13	341	3.18777E-13	3.18743E-13
NA0805	73	4.11388E-13	4.11384E-13	287	4.53696E-13	4.53692E-13
NA0806	74	2.22117E-12	2.22058E-12	311	2.53274E-12	2.53197E-12
NA0807	58	3.80922E-12	3.80924E-12	258	4.36398E-12	4.36401E-12
NA0808	92	1.02264E-12	1.02262E-12	278	1.18340E-12	1.18338E-12
NA0809	63	1.51935E-12	-	256	1.88517E-12	-
NA0810	88	3.64779E-13	3.64780E-13	312	4.14776E-13	4.14776E-13
NA0811	98	1.26125E-13	1.26125E-13	323	1.52040E-13	1.52041E-13
NA0812	62	1.06950E-12	1.06950E-12	262	1.19070E-12	1.19069E-12
NA0813	94	1.97047E-12	1.97048E-12	253	2.11053E-12	2.11054E-12
NA0814	68	2.74106E-12	2.74007E-12	319	3.03093E-12	3.02972E-12
NA0815	136	2.82308E-13	2.82303E-13	355	3.06766E-13	3.06759E-13
NA1101	44	3.16602E-13	3.16601E-13	215	4.58767E-13	4.58765E-13
NA1102	5	-	-	132	-	-
NA1103	26	-	-	131	-	-
NA1104	27	-	-	147	-	-
NA1105	6	-	-	33	-	-
NA1106	34	-	-	212	-	-
NA1107	32	-	-	189	-	-
NA1108	35	-	-	149	-	-
NA1109	6	-	-	49	-	-
NA1110	8	-	-	54	-	-
NA1111	54	1.71172E-13	1.71172E-13	198	2.52451E-13	2.52452E-13
NA1112	6	-	-	55	-	-
NA1113	4	-	-	53	-	-

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Distribution
NA1114	34	-	-	150	-	-
NA1115	19	-	-	86	-	-
NA1116	46	-	1.81543E-13	165	-	2.84819E-13
NA1117	47	5.35059E-13	5.35059E-13	232	7.81642E-13	7.81641E-13
NA1118	19	-	-	80	-	-
NA1201	81	4.03538E-12	4.03499E-12	356	4.08460E-12	4.08420E-12
NA1202	106	2.01053E-12	2.01031E-12	336	2.05749E-12	2.05727E-12
NA1203	96	6.82156E-12	6.82099E-12	340	6.92826E-12	6.92768E-12
NA1301	67	2.10315E-12	2.10325E-12	325	2.11913E-12	2.11924E-12
NA1302	162	3.08125E-12	3.08227E-12	402	3.08439E-12	3.08541E-12
NA1303	179	3.04608E-13	3.04589E-13	429	3.11669E-13	3.11650E-13
NA1304	151	3.92750E-13	3.92734E-13	334	4.12257E-13	4.12240E-13
NA1305	124	3.57405E-13	3.57397E-13	298	3.69304E-13	3.69296E-13
NA1306	56	7.11913E-12	7.11958E-12	271	7.13239E-12	7.13285E-12
NA1307	183	1.40977E-12	1.41036E-12	468	1.41355E-12	1.41415E-12
NA1308	124	1.04137E-12	1.04124E-12	310	1.06101E-12	1.06087E-12
NA1309	125	4.80140E-13	4.80136E-13	283	5.03634E-13	5.03630E-13
NA1310	150	6.72404E-13	6.72325E-13	426	6.80572E-13	6.80491E-13
NA1311	108	1.05198E-11	1.05227E-11	407	1.06434E-11	1.06463E-11
NA1312	121	1.15238E-12	1.15220E-12	440	1.17872E-12	1.17853E-12
NA1313	99	8.02301E-13	8.02301E-13	271	8.65070E-13	8.65070E-13
NT0101	187	1.25964E-12	1.25957E-12	680	1.26450E-12	1.26442E-12
NT0102	220	3.56877E-11	3.56877E-11	825	3.55982E-11	3.55983E-11
NT0103	195	2.86223E-12	2.86237E-12	707	2.86556E-12	2.86570E-12
NT0104	243	1.34052E-12	1.34051E-12	822	1.33941E-12	1.33940E-12
NT0105	290	3.47843E-12	3.47868E-12	1212	3.50319E-12	3.50345E-12
NT0106	128	7.10229E-11	7.10466E-11	364	7.05265E-11	7.05499E-11
NT0107	234	-	1.87266E-12	754	-	1.86941E-12
NT0108	219	1.47035E-11	1.47067E-11	736	1.46493E-11	1.46525E-11
NT0109	242	1.06624E-11	1.06659E-11	968	1.06495E-11	1.06530E-11
NT0110	2	-	-	100	-	-
NT0111	205	3.60296E-12	3.60336E-12	718	3.59577E-12	3.59616E-12
NT0112	205	2.42568E-11	2.42677E-11	689	2.41816E-11	2.41925E-11
NT0113	172	5.45774E-11	5.46266E-11	559	5.44556E-11	5.45046E-11
NT0114	142	-	1.51430E-10	514	-	1.51142E-10
NT0115	257	4.63143E-12	4.63253E-12	1000	4.62781E-12	4.62891E-12
NT0116	0	-	-	41	-	-
NT0117	196	2.32866E-11	2.32938E-11	721	2.31793E-11	2.31864E-11
NT0118	305	5.01360E-12	5.01428E-12	1280	5.00519E-12	5.00586E-12
NT0119	198	3.11793E-11	3.11885E-11	720	3.11099E-11	3.11191E-11
NT0120	30	1.05085E-11	1.05119E-11	261	1.04733E-11	1.04767E-11
NT0121	344	3.34555E-12	3.34645E-12	1421	3.34879E-12	3.34969E-12
NT0122	193	-	1.11107E-10	638	-	1.10976E-10
NT0123	0	-	-	35	-	-
NT0124	263	2.34020E-12	2.34019E-12	910	2.33410E-12	2.33410E-12

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Distribution
NT0125	244	7.17222E-13	7.17241E-13	895	7.14532E-13	7.14550E-13
NT0126	199	3.47578E-11	3.47616E-11	703	3.47171E-11	3.47210E-11
NT0127	20	5.04156E-12	5.04341E-12	221	5.02165E-12	5.02349E-12
NT0128	311	2.96326E-12	2.96332E-12	976	2.96227E-12	2.96233E-12
NT0129	232	5.69968E-12	5.70011E-12	898	5.69040E-12	5.69083E-12
NT0130	198	1.15178E-11	1.15200E-11	780	1.14979E-11	1.15001E-11
NT0131	22	2.81896E-11	2.82084E-11	217	2.80786E-11	2.80972E-11
NT0132	259	1.27965E-12	1.27966E-12	812	1.27823E-12	1.27824E-12
NT0133	220	-	-	705	-	-
NT0134	15	-	2.40418E-10	177	-	2.38761E-10
NT0135	322	4.66223E-13	4.66232E-13	1039	4.65677E-13	4.65686E-13
NT0136	295	3.24849E-12	3.24907E-12	1161	3.24102E-12	3.24160E-12
NT0137	223	4.39751E-12	4.39796E-12	755	4.38703E-12	4.38748E-12
NT0138	212	3.89044E-12	3.89071E-12	813	3.87988E-12	3.88015E-12
NT0139	154	2.40892E-12	2.40937E-12	592	2.40158E-12	2.40202E-12
NT0140	230	8.05590E-13	8.05583E-13	826	8.04327E-13	8.04320E-13
NT0141	286	5.13079E-12	5.13098E-12	943	5.12540E-12	5.12559E-12
NT0142	314	1.36739E-12	1.36754E-12	1102	1.36818E-12	1.36833E-12
NT0143	243	-	-	794	-	-
NT0144	117	3.41808E-11	3.41891E-11	418	3.40059E-11	3.40141E-11
NT0145	309	4.22187E-12	4.22295E-12	1197	4.22073E-12	4.22181E-12
NT0146	193	4.04463E-11	4.04728E-11	630	4.06481E-11	4.06749E-11
NT0147	208	-	1.19628E-11	686	-	1.19220E-11
NT0148	131	1.80930E-11	1.80959E-11	458	1.79571E-11	1.79599E-11
NT0149	182	4.42473E-11	4.42539E-11	627	4.40913E-11	4.40979E-11
NT0150	286	5.88728E-13	5.88731E-13	905	5.90807E-13	5.90810E-13
NT0151	136	1.90872E-11	1.90862E-11	469	1.90334E-11	1.90324E-11
NT0152	149	1.47578E-11	1.47582E-11	481	1.47256E-11	1.47260E-11
NT0153	346	1.76812E-12	1.76829E-12	1466	1.77445E-12	1.77462E-12
NT0154	242	2.10079E-12	2.10111E-12	754	2.10016E-12	2.10048E-12
NT0155	13	3.10736E-11	3.10433E-11	195	3.08740E-11	3.08441E-11
NT0156	296	-	1.93160E-12	873	-	1.92991E-12
NT0157	234	1.95431E-12	1.95438E-12	802	1.95304E-12	1.95311E-12
NT0158	242	3.57810E-12	3.57809E-12	752	3.57341E-12	3.57340E-12
NT0159	168	-	6.94273E-11	606	-	6.89459E-11
NT0160	214	2.69067E-12	2.68998E-12	832	2.68681E-12	2.68612E-12
NT0161	112	7.92785E-11	7.93070E-11	463	7.87839E-11	7.88121E-11
NT0162	159	2.85660E-11	2.85788E-11	506	2.83628E-11	2.83754E-11
NT0163	239	-	-	696	-	-
NT0164	31	1.15435E-10	1.15431E-10	265	1.31623E-10	1.31617E-10
NT0165	220	3.65204E-12	3.65237E-12	681	3.75555E-12	3.75590E-12
NT0166	411	4.44135E-13	4.44145E-13	1496	4.44470E-13	4.44480E-13
NT0167	218	2.05534E-11	2.05544E-11	791	2.05133E-11	2.05143E-11
NT0168	216	1.01376E-12	1.01377E-12	785	1.01263E-12	1.01264E-12
NT0169	255	6.73500E-12	-	861	6.71869E-12	-

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Distribution
NT0170	178	1.77721E-12	1.77745E-12	686	1.77175E-12	1.77198E-12
NT0171	80	-	5.28572E-11	376	-	5.27197E-11
NT0172	0	-	-	21	-	-
NT0173	270	7.31117E-13	7.31122E-13	937	7.29724E-13	7.29729E-13
NT0174	287	2.94173E-12	2.94217E-12	1206	2.94719E-12	2.94763E-12
NT0175	228	1.14420E-11	1.14447E-11	804	1.13947E-11	1.13973E-11
NT0176	187	4.19361E-12	4.19456E-12	595	4.23431E-12	4.23528E-12
NT0177	141	5.94669E-11	5.95309E-11	483	6.02704E-11	6.03361E-11
NT0178	191	1.00974E-11	1.01017E-11	751	1.00859E-11	1.00902E-11
NT0179	27	-	1.20288E-10	175	-	1.19766E-10
NT0180	199	1.28137E-12	1.28137E-12	780	1.27809E-12	1.27809E-12
NT0181	120	4.39818E-12	4.39843E-12	463	4.38241E-12	4.38266E-12
NT0182	257	1.48610E-12	1.48609E-12	881	1.48271E-12	1.48270E-12
NT0201	280	4.94644E-12	4.94668E-12	1015	4.94072E-12	4.94096E-12
NT0202	172	2.80951E-12	2.80972E-12	519	2.81647E-12	2.81668E-12
NT0204	153	7.88292E-12	7.88332E-12	398	7.92145E-12	7.92187E-12
NT0205	200	4.92243E-12	4.92431E-12	549	4.92799E-12	4.92988E-12
NT0206	269	4.12088E-12	4.12098E-12	1079	4.18857E-12	4.18867E-12
NT0207	212	4.66469E-11	4.66431E-11	739	4.64801E-11	4.64764E-11
NT0209	242	4.79789E-12	4.79854E-12	903	4.78656E-12	4.78721E-12
NT0210	273	2.17470E-13	2.17479E-13	839	2.18152E-13	2.18161E-13
NT0211	175	2.26464E-11	2.26497E-11	566	2.25819E-11	2.25852E-11
NT0212	243	1.37053E-12	1.37052E-12	858	1.37227E-12	1.37226E-12
NT0213	31	3.39229E-12	3.39275E-12	279	3.37882E-12	3.37928E-12
NT0214	150	1.21630E-11	1.21714E-11	587	1.21601E-11	1.21685E-11
NT0215	20	1.49651E-11	1.49687E-11	223	1.49121E-11	1.49157E-11
NT0216	0	-	-	61	-	-
NT0217	147	1.15782E-11	1.15815E-11	515	1.15728E-11	1.15761E-11
NT0218	21	1.01091E-10	1.01161E-10	207	1.00712E-10	1.00781E-10
NT0219	175	1.96188E-11	1.96242E-11	551	1.95202E-11	1.95256E-11
NT0220	91	-	2.69067E-10	429	-	2.68537E-10
NT0221	232	1.74863E-11	1.74877E-11	758	1.74124E-11	1.74138E-11
NT0222	207	1.10636E-11	1.10640E-11	694	1.10149E-11	1.10153E-11
NT0223	192	-	2.98473E-11	781	-	2.98787E-11
NT0224	163	6.61721E-11	6.61749E-11	684	6.59873E-11	6.59901E-11
NT0225	183	1.51649E-10	1.51652E-10	544	1.50810E-10	1.50813E-10
NT0226	13	1.83786E-10	1.83681E-10	186	1.82741E-10	1.82637E-10
NT0227	43	6.86915E-11	6.86807E-11	243	6.98171E-11	6.98060E-11
NT0228	167	3.61120E-12	3.61169E-12	517	3.63187E-12	3.63236E-12
NT0229	183	1.33643E-11	1.33644E-11	680	1.33034E-11	1.33034E-11
NT0230	198	7.43968E-12	7.44314E-12	691	7.42657E-12	7.43002E-12
NT0232	152	8.25677E-12	8.25930E-12	681	8.23606E-12	8.23858E-12
NT0233	128	4.59833E-11	4.59854E-11	466	4.58597E-11	4.58617E-11
NT0235	90	6.02571E-12	6.02542E-12	381	6.02435E-12	6.02405E-12
NT0301	10	3.12449E-11	3.12534E-11	231	3.10975E-11	3.11059E-11

Ecoregion code	No. of mammals	Mammals		No. of birds	Birds	
		Regional CF [PDF*y/m2]			Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
NT0302	119	1.10851E-10	1.10835E-10	484	1.10601E-10	1.10585E-10
NT0303	237	2.89670E-12	2.89812E-12	736	2.88807E-12	2.88948E-12
NT0304	28	3.46931E-11	3.47010E-11	249	3.45707E-11	3.45785E-11
NT0305	20	-	2.00061E-11	204	-	1.98983E-11
NT0306	118	-	1.70588E-11	484	-	1.70073E-11
NT0307	42	-	-	209	-	-
NT0308	195	2.17698E-11	2.17799E-11	656	2.18289E-11	2.18392E-11
NT0309	178	5.10287E-12	5.10587E-12	523	5.08442E-12	5.08739E-12
NT0310	237	3.24652E-12	3.24716E-12	658	3.27298E-12	3.27362E-12
NT0401	0	-	-	40	-	-
NT0402	40	-	-	204	-	-
NT0403	0	-	-	32	-	-
NT0404	79	7.08380E-13	7.08408E-13	263	7.00024E-13	7.00051E-13
NT0702	235	1.58599E-12	1.58601E-12	843	1.58594E-12	1.58596E-12
NT0703	236	7.13237E-12	7.13308E-12	780	7.13175E-12	7.13246E-12
NT0704	388	1.02404E-13	1.02401E-13	1131	1.02410E-13	1.02407E-13
NT0705	0	-	-	27	-	-
NT0707	243	2.01205E-12	2.01208E-12	878	2.01179E-12	2.01183E-12
NT0708	168	5.78148E-13	5.78192E-13	643	5.80759E-13	5.80803E-13
NT0709	298	5.53326E-13	5.53334E-13	1041	5.53283E-13	5.53291E-13
NT0710	132	4.32768E-13	4.32761E-13	611	4.33806E-13	4.33799E-13
NT0801	117	4.63687E-13	4.63688E-13	496	4.75489E-13	4.75490E-13
NT0802	76	3.46951E-13	3.46935E-13	317	3.55373E-13	3.55356E-13
NT0803	88	3.27090E-13	3.27090E-13	413	3.45348E-13	3.45348E-13
NT0805	81	1.69319E-13	1.69318E-13	325	1.71217E-13	1.71217E-13
NT0902	29	3.92405E-11	3.92447E-11	253	3.91014E-11	3.91057E-11
NT0903	18	-	3.69612E-10	200	-	3.67897E-10
NT0904	36	7.97695E-12	7.97676E-12	277	8.47777E-12	8.47754E-12
NT0905	124	7.20767E-11	7.20753E-11	418	7.20646E-11	7.20633E-11
NT0906	172	3.42802E-11	3.42797E-11	498	3.42598E-11	3.42592E-11
NT0907	190	1.11756E-12	1.11758E-12	651	1.11766E-12	1.11768E-12
NT0908	120	4.13346E-12	4.13351E-12	499	4.14106E-12	4.14111E-12
NT0909	106	6.02786E-12	6.02771E-12	471	6.04159E-12	6.04143E-12
NT1001	146	7.07356E-13	7.07375E-13	377	7.09695E-13	7.09715E-13
NT1002	258	8.62250E-13	8.62252E-13	799	8.66820E-13	8.66822E-13
NT1003	266	1.70324E-12	1.70324E-12	1089	1.70476E-12	1.70477E-12
NT1004	205	1.71053E-11	1.71060E-11	836	1.71044E-11	1.71051E-11
NT1005	206	-	7.36849E-11	645	-	7.36557E-11
NT1006	380	7.04499E-12	7.04525E-12	1457	7.04518E-12	7.04544E-12
NT1007	157	-	1.64370E-10	559	-	1.64286E-10
NT1008	99	1.19917E-12	1.19917E-12	251	1.20570E-12	1.20570E-12
NT1010	130	1.35232E-12	1.35237E-12	329	1.36011E-12	1.36017E-12
NT1201	54	1.02151E-12	1.02153E-12	259	1.01142E-12	1.01144E-12
NT1301	166	3.87759E-11	3.87909E-11	534	3.87596E-11	3.87745E-11
NT1303	39	1.51124E-12	1.51124E-12	229	1.66474E-12	1.66473E-12

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Mammals Regional CF [PDF*y/m2] Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Birds Regional CF [PDF*y/m2] Distribution
NT1304	207	2.81237E-13	2.81270E-13	715	2.81263E-13	2.81296E-13
NT1305	36	7.68794E-11	7.69256E-11	257	7.63259E-11	7.63714E-11
NT1306	29	6.92447E-11	6.92768E-11	253	6.89994E-11	6.90312E-11
NT1307	6	-	-	117	-	-
NT1308	197	6.45748E-12	6.45775E-12	687	6.45584E-12	6.45611E-12
NT1309	207	3.00757E-12	3.00743E-12	760	3.00678E-12	3.00664E-12
NT1311	0	-	-	47	-	-
NT1312	150	8.45998E-11	8.46100E-11	531	8.45923E-11	8.46025E-11
NT1313	190	1.27969E-11	1.28007E-11	631	1.27925E-11	1.27963E-11
NT1314	46	4.54619E-11	4.54719E-11	254	4.56431E-11	4.56532E-11
NT1315	140	1.07382E-12	1.07385E-12	466	1.07269E-12	1.07272E-12
NT1316	161	1.91540E-11	1.91575E-11	506	1.91772E-11	1.91807E-11
NT1318	0	-	-	24	-	-
NT1401	362	8.27953E-12	8.28123E-12	1274	8.26547E-12	8.26716E-12
NT1402	60	1.23920E-11	1.23939E-11	425	1.23747E-11	1.23765E-11
NT1403	254	1.15640E-11	1.15648E-11	840	1.15461E-11	1.15469E-11
NT1404	181	3.47604E-11	3.47630E-11	503	3.47171E-11	3.47197E-11
NT1405	240	2.53653E-11	2.53668E-11	839	2.53022E-11	2.53037E-11
NT1406	245	3.08106E-11	3.08086E-11	854	3.07525E-11	3.07505E-11
NT1407	209	4.16600E-11	4.16642E-11	656	4.15164E-11	4.15207E-11
OC0101	4	-	-	103	-	-
OC0102	0	-	-	62	-	-
OC0103	1	-	-	54	-	-
OC0104	0	-	-	69	-	-
OC0105	6	-	-	117	-	-
OC0106	1	-	-	111	-	-
OC0107	0	-	-	67	-	-
OC0108	0	-	-	58	-	-
OC0109	1	-	-	48	-	-
OC0110	1	-	-	95	-	-
OC0111	0	-	-	29	-	-
OC0112	2	-	-	81	-	-
OC0113	1	-	-	57	-	-
OC0114	1	2.44067E-10	2.44150E-10	73	2.43207E-10	2.43290E-10
OC0115	0	-	-	62	-	-
OC0116	1	-	-	47	-	-
OC0117	0	-	-	59	-	-
OC0201	4	-	-	101	-	-
OC0202	1	-	-	108	-	-
OC0203	2	-	-	85	-	-
OC0204	1	-	-	63	-	-
OC0701	1	-	-	66	-	-
OC0702	1	-	-	97	-	-
OC0703	0	-	-	84	-	-
PA0101	165	9.65437E-13	9.65751E-13	518	9.56266E-13	9.56574E-13

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2]		No. of birds	Birds Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
PA0102	217	1.13849E-12	1.13853E-12	707	1.13532E-12	1.13537E-12
PA0401	64	9.14127E-12	9.14002E-12	208	9.26598E-12	9.26469E-12
PA0402	77	2.89305E-13	2.89292E-13	321	3.01378E-13	3.01364E-13
PA0403	2	-	-	51	-	-
PA0404	97	6.45716E-13	6.45726E-13	320	6.73943E-13	6.73954E-13
PA0405	55	8.03967E-13	8.03968E-13	258	8.40352E-13	8.40352E-13
PA0406	71	1.89550E-12	1.89488E-12	283	1.93781E-12	1.93716E-12
PA0407	102	3.11000E-12	3.11021E-12	337	3.08792E-12	3.08813E-12
PA0408	122	8.67458E-13	8.67482E-13	318	8.90827E-13	8.90852E-13
PA0409	40	3.90226E-13	3.90222E-13	245	4.01001E-13	4.00997E-13
PA0410	70	1.59718E-12	1.59717E-12	304	1.66386E-12	1.66385E-12
PA0411	146	5.06640E-13	5.06654E-13	453	5.43998E-13	5.44014E-13
PA0412	95	1.41077E-13	1.41069E-13	305	1.53405E-13	1.53395E-13
PA0413	53	1.79726E-12	1.79729E-12	292	1.95241E-12	1.95245E-12
PA0414	73	1.69341E-12	1.69359E-12	278	1.88031E-12	1.88053E-12
PA0415	112	5.40928E-13	5.40958E-13	478	5.52199E-13	5.52230E-13
PA0416	76	4.17768E-12	4.17731E-12	275	4.70119E-12	4.70072E-12
PA0417	149	1.39253E-12	1.39281E-12	464	1.40186E-12	1.40216E-12
PA0418	87	2.37025E-12	2.37013E-12	280	2.56640E-12	2.56626E-12
PA0419	111	1.21134E-13	1.21131E-13	328	1.42430E-13	1.42425E-13
PA0420	72	1.78097E-12	1.78102E-12	277	2.01193E-12	2.01199E-12
PA0421	36	1.96749E-12	1.96745E-12	218	2.03190E-12	2.03186E-12
PA0422	98	2.11014E-12	2.11069E-12	321	2.10545E-12	2.10600E-12
PA0423	37	5.14722E-12	5.14552E-12	234	5.23937E-12	5.23761E-12
PA0424	130	4.66903E-13	4.66906E-13	459	4.90409E-13	4.90412E-13
PA0425	3	-	-	61	-	-
PA0426	97	2.59997E-13	2.60002E-13	376	2.89272E-13	2.89279E-13
PA0427	45	7.27394E-12	7.27143E-12	245	7.57686E-12	7.57413E-12
PA0428	62	1.80739E-12	1.80685E-12	280	1.88139E-12	1.88080E-12
PA0429	30	1.78047E-12	1.78047E-12	219	1.90675E-12	1.90675E-12
PA0430	92	6.46338E-13	6.46335E-13	351	6.99459E-13	6.99455E-13
PA0431	92	3.88413E-13	3.88400E-13	275	4.40833E-13	4.40817E-13
PA0432	79	3.02811E-12	3.02800E-12	289	3.37502E-12	3.37488E-12
PA0433	69	5.71746E-12	5.71645E-12	228	5.78685E-12	5.78582E-12
PA0434	156	1.72878E-12	1.72916E-12	431	1.82322E-12	1.82365E-12
PA0435	80	4.69774E-12	4.69783E-12	282	4.88186E-12	4.88196E-12
PA0436	80	9.46812E-14	9.46700E-14	305	1.03646E-13	1.03632E-13
PA0437	151	2.49361E-12	2.49370E-12	427	2.50030E-12	2.50039E-12
PA0438	39	9.34741E-12	9.34622E-12	233	9.76102E-12	9.75972E-12
PA0439	38	1.29916E-11	1.29892E-11	262	1.47349E-11	1.47317E-11
PA0440	49	1.21702E-12	1.21637E-12	288	1.24871E-12	1.24804E-12
PA0441	47	3.87062E-12	3.86844E-12	274	3.91953E-12	3.91729E-12
PA0442	40	-	1.93392E-12	134	-	2.87032E-12
PA0443	72	6.68277E-13	6.68259E-13	313	7.55424E-13	7.55401E-13
PA0444	79	3.66629E-13	3.66618E-13	280	3.88409E-13	3.88397E-13

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Mammals Regional CF [PDF*y/m2] Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Birds Regional CF [PDF*y/m2] Distribution
PA0445	92	2.42013E-13	2.41994E-13	287	2.56053E-13	2.56032E-13
PA0446	115	4.79818E-13	4.79828E-13	363	4.73639E-13	4.73648E-13
PA0501	89	8.51965E-13	8.51761E-13	278	9.08907E-13	9.08675E-13
PA0502	128	7.65642E-13	7.65641E-13	341	8.35793E-13	8.35792E-13
PA0503	26	3.03507E-12	3.03505E-12	191	3.18423E-12	3.18421E-12
PA0504	84	9.44067E-13	9.44007E-13	247	1.02476E-12	1.02469E-12
PA0505	79	4.01862E-13	4.01854E-13	292	4.52418E-13	4.52408E-13
PA0506	91	9.79775E-12	9.79789E-12	348	9.96401E-12	9.96415E-12
PA0507	112	2.73772E-12	2.73775E-12	320	2.68539E-12	2.68542E-12
PA0508	63	-	-	186	-	-
PA0509	176	2.42017E-12	2.42029E-12	542	2.51981E-12	2.51994E-12
PA0510	38	2.82886E-12	2.82824E-12	239	2.89555E-12	2.89490E-12
PA0511	60	1.31273E-11	1.31253E-11	239	1.34617E-11	1.34597E-11
PA0512	50	-	-	208	-	-
PA0513	71	8.32018E-12	8.32137E-12	306	7.74059E-12	7.74162E-12
PA0514	140	5.06903E-12	5.06932E-12	597	5.45307E-12	5.45340E-12
PA0515	82	1.62671E-12	1.62688E-12	289	1.54242E-12	1.54257E-12
PA0516	242	3.00309E-12	3.00312E-12	680	3.06324E-12	3.06327E-12
PA0517	123	1.06927E-11	1.06929E-11	331	1.24303E-11	1.24306E-11
PA0518	201	2.94906E-12	2.94968E-12	526	3.02159E-12	3.02225E-12
PA0519	96	2.78002E-13	2.77997E-13	342	2.82468E-13	2.82463E-13
PA0520	33	2.55400E-12	2.55367E-12	228	3.00305E-12	3.00261E-12
PA0521	101	4.38957E-12	4.38959E-12	319	5.25639E-12	5.25641E-12
PA0601	98	1.52817E-14	1.52817E-14	388	1.58056E-14	1.58055E-14
PA0602	2	4.66403E-13	4.66403E-13	84	4.69443E-13	4.69443E-13
PA0603	33	5.49525E-13	5.49525E-13	215	6.85752E-13	6.85753E-13
PA0604	30	4.86327E-12	4.86335E-12	131	6.22628E-12	6.22643E-12
PA0605	46	3.95886E-14	3.95887E-14	231	4.48326E-14	4.48328E-14
PA0606	69	2.65561E-13	2.65560E-13	305	2.94860E-13	2.94859E-13
PA0607	39	1.36968E-12	1.36959E-12	225	1.46855E-12	1.46845E-12
PA0608	76	2.55478E-14	2.55463E-14	307	2.77547E-14	2.77529E-14
PA0609	81	5.13370E-13	5.13362E-13	285	5.49074E-13	5.49065E-13
PA0610	64	3.54370E-13	3.54355E-13	265	4.02150E-13	4.02130E-13
PA0611	76	3.52838E-14	3.52827E-14	304	3.79256E-14	3.79243E-14
PA0801	81	8.04512E-13	8.04512E-13	321	8.59963E-13	8.59963E-13
PA0802	105	9.54609E-13	9.54609E-13	319	1.01495E-12	1.01495E-12
PA0803	52	4.56293E-12	4.56293E-12	283	4.77217E-12	4.77217E-12
PA0804	88	3.76970E-13	3.76968E-13	295	3.92421E-13	3.92418E-13
PA0805	116	7.09034E-13	7.09036E-13	325	6.98771E-13	6.98774E-13
PA0806	83	-	1.22198E-12	292	-	1.41506E-12
PA0807	1	-	-	63	-	-
PA0808	98	6.22783E-13	6.22786E-13	341	6.79831E-13	6.79835E-13
PA0809	102	1.53256E-13	1.53251E-13	327	1.58696E-13	1.58691E-13
PA0810	104	8.68911E-14	8.68910E-14	311	9.25677E-14	9.25677E-14
PA0811	68	8.87120E-13	8.87120E-13	253	1.07865E-12	1.07865E-12

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Mammals Regional CF [PDF*y/m2] Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Birds Regional CF [PDF*y/m2] Distribution
PA0812	96	1.03057E-12	1.03057E-12	343	9.67052E-13	9.67053E-13
PA0813	128	1.06443E-13	1.06443E-13	388	1.11301E-13	1.11301E-13
PA0814	143	8.23544E-14	8.23539E-14	348	8.74160E-14	8.74154E-14
PA0815	73	2.18302E-12	2.18304E-12	282	2.21966E-12	2.21968E-12
PA0816	102	3.63307E-13	3.63306E-13	325	3.68389E-13	3.68387E-13
PA0817	73	4.05184E-13	4.05147E-13	286	4.02614E-13	4.02577E-13
PA0818	102	7.21617E-13	7.21617E-13	328	8.03642E-13	8.03643E-13
PA0901	72	7.03298E-13	7.03283E-13	276	7.29066E-13	7.29049E-13
PA0902	37	1.01404E-11	1.01409E-11	269	1.11205E-11	1.11211E-11
PA0903	61	-	3.95741E-12	226	-	4.17549E-12
PA0904	61	3.14241E-12	3.14236E-12	284	2.87613E-12	2.87610E-12
PA0905	83	-	2.85756E-12	316	-	2.64533E-12
PA0906	49	4.00318E-12	4.00319E-12	270	3.85223E-12	3.85224E-12
PA0907	71	2.92762E-12	2.92760E-12	282	3.07195E-12	3.07192E-12
PA0908	32	-	2.37280E-11	257	-	2.68505E-11
PA1001	118	8.85917E-13	8.85914E-13	342	9.38699E-13	9.38696E-13
PA1002	109	2.07325E-13	2.07312E-13	294	2.24793E-13	2.24780E-13
PA1003	247	-	1.33131E-12	776	-	1.34131E-12
PA1004	83	-	-	282	-	-
PA1005	82	-	4.47459E-12	314	-	4.56243E-12
PA1006	99	8.93795E-13	8.93796E-13	350	9.46751E-13	9.46751E-13
PA1007	65	-	-	227	-	-
PA1008	83	-	2.03820E-12	270	-	2.03106E-12
PA1009	102	1.11941E-12	1.11941E-12	306	1.08864E-12	1.08864E-12
PA1010	67	-	2.30425E-11	240	-	2.17121E-11
PA1011	69	-	-	182	-	-
PA1012	123	2.65736E-12	2.65742E-12	473	2.86441E-12	2.86448E-12
PA1013	118	5.67978E-13	5.67978E-13	303	5.90456E-13	5.90456E-13
PA1014	91	-	9.22316E-13	305	-	1.00314E-12
PA1015	72	-	-	200	-	-
PA1016	98	8.94901E-13	8.94905E-13	327	9.19895E-13	9.19899E-13
PA1017	243	3.17473E-13	3.17481E-13	578	3.22567E-13	3.22575E-13
PA1018	89	6.07867E-12	6.07870E-12	350	6.04663E-12	6.04667E-12
PA1019	116	3.28090E-13	3.28090E-13	346	3.74179E-13	3.74178E-13
PA1020	93	4.35547E-13	-	287	5.22333E-13	-
PA1021	124	2.11752E-12	2.11754E-12	511	2.21692E-12	2.21694E-12
PA1022	79	-	2.48313E-12	257	-	2.62897E-12
PA1101	4	-	-	49	-	-
PA1102	36	1.09330E-13	1.09330E-13	184	1.23888E-13	1.23888E-13
PA1103	45	-	7.95742E-14	217	-	8.74411E-14
PA1104	30	-	1.15674E-13	157	-	1.34996E-13
PA1105	32	6.09092E-13	6.09093E-13	174	7.75748E-13	7.75749E-13
PA1106	22	5.73696E-13	5.73689E-13	165	6.70478E-13	6.70468E-13
PA1107	29	-	-	119	-	-
PA1108	37	1.27268E-13	1.27268E-13	198	1.33723E-13	1.33723E-13

Ecoregion code	No. of mammals	Mammals Regional CF [PDF*y/m2] Transmission	Mammals Regional CF [PDF*y/m2] Distribution	No. of birds	Birds Regional CF [PDF*y/m2] Transmission	Birds Regional CF [PDF*y/m2] Distribution
PA1109	4	-	-	42	-	-
PA1110	40	1.80045E-13	1.80038E-13	237	1.99796E-13	1.99787E-13
PA1111	37	2.71626E-14	2.71626E-14	170	2.52293E-14	2.52293E-14
PA1112	66	3.87498E-13	3.87497E-13	294	4.31307E-13	4.31305E-13
PA1113	3	-	-	36	-	-
PA1114	36	8.57516E-14	8.57517E-14	152	8.11475E-14	8.11477E-14
PA1201	102	8.96348E-13	8.96423E-13	322	9.04655E-13	9.04732E-13
PA1202	75	1.38220E-12	1.38247E-12	303	1.38135E-12	1.38162E-12
PA1203	8	-	-	115	-	-
PA1204	32	3.40349E-11	3.40307E-11	163	3.39892E-11	3.39850E-11
PA1205	30	1.96342E-11	1.96373E-11	159	1.79660E-11	1.79686E-11
PA1206	25	1.53772E-11	1.53789E-11	204	1.63015E-11	1.63034E-11
PA1207	121	9.21665E-13	9.21749E-13	380	8.91471E-13	8.91550E-13
PA1208	62	3.39241E-12	3.39285E-12	241	3.30772E-12	3.30814E-12
PA1209	74	3.93359E-13	3.93341E-13	290	3.90759E-13	3.90741E-13
PA1210	86	2.62501E-12	2.62449E-12	304	2.70685E-12	2.70630E-12
PA1211	79	1.00847E-12	1.00810E-12	290	1.05087E-12	1.05047E-12
PA1212	76	1.53278E-12	1.53283E-12	315	1.45884E-12	1.45888E-12
PA1213	99	4.94055E-13	4.94056E-13	354	4.64945E-13	4.64946E-13
PA1214	98	3.93103E-13	3.93135E-13	348	3.73860E-13	3.73889E-13
PA1215	90	1.15522E-12	1.15466E-12	309	1.18942E-12	1.18883E-12
PA1216	68	1.89243E-12	1.89256E-12	244	1.91592E-12	1.91605E-12
PA1217	83	2.89682E-12	2.89723E-12	282	2.92444E-12	2.92486E-12
PA1218	60	9.24362E-12	9.24100E-12	204	8.82062E-12	8.81823E-12
PA1219	41	4.23649E-11	4.23537E-11	231	4.35555E-11	4.35436E-11
PA1220	94	1.67168E-12	1.67215E-12	340	1.63278E-12	1.63324E-12
PA1221	58	1.69218E-12	1.69182E-12	289	1.73649E-12	1.73612E-12
PA1222	79	1.62774E-12	1.62711E-12	303	1.64292E-12	1.64227E-12
PA1301	69	-	-	266	-	-
PA1302	126	1.52905E-13	-	313	1.67408E-13	-
PA1303	103	9.19615E-14	9.19615E-14	403	8.51154E-14	8.51154E-14
PA1304	48	-	-	274	-	-
PA1305	91	1.80451E-12	1.80455E-12	313	1.75813E-12	1.75817E-12
PA1306	92	9.04524E-13	9.04524E-13	296	9.25014E-13	9.25014E-13
PA1307	144	5.08966E-13	5.08968E-13	572	5.28991E-13	5.28993E-13
PA1308	107	3.40105E-13	-	328	3.45066E-13	-
PA1309	92	-	-	330	-	-
PA1310	112	1.39509E-13	1.39510E-13	344	1.49467E-13	1.49467E-13
PA1311	86	1.05674E-12	1.05674E-12	303	1.14126E-12	1.14126E-12
PA1312	92	1.90757E-13	1.90756E-13	309	1.94499E-13	1.94498E-13
PA1313	124	2.37195E-13	2.37195E-13	343	2.35513E-13	2.35513E-13
PA1314	86	-	-	200	-	-
PA1315	74	-	-	204	-	-
PA1316	101	5.05176E-13	5.05176E-13	303	5.39547E-13	5.39546E-13
PA1317	126	2.94554E-13	2.94553E-13	335	3.09397E-13	3.09395E-13

Ecoregion code	No. of mammals	Mammals		No. of birds	Birds	
		Regional CF [PDF*y/m2]			Regional CF [PDF*y/m2]	
		Transmission	Distribution		Transmission	Distribution
PA1318	100	-	-	313	-	-
PA1319	77	-	-	279	-	-
PA1320	97	6.63587E-13	6.63587E-13	344	6.24133E-13	6.24133E-13
PA1321	119	9.55491E-14	9.55490E-14	404	8.95015E-14	8.95014E-14
PA1322	93	-	1.27585E-12	317	-	1.37819E-12
PA1323	34	2.15316E-12	2.15316E-12	267	2.07726E-12	2.07726E-12
PA1324	60	-	-	181	-	-
PA1325	74	2.66038E-13	2.66039E-13	347	2.44310E-13	2.44311E-13
PA1326	74	-	4.95160E-13	274	-	5.12265E-13
PA1327	92	3.74966E-14	3.74966E-14	370	3.44471E-14	3.44470E-14
PA1328	95	4.36191E-13	4.36192E-13	382	4.34773E-13	4.34774E-13
PA1329	89	-	1.68708E-13	361	-	1.56099E-13
PA1330	110	1.29973E-13	1.29973E-13	275	1.51609E-13	1.51609E-13
PA1331	18	-	-	76	-	-
PA1332	60	-	-	195	-	-
PA1333	47	-	-	259	-	-

Table B2. List of Countries with Regional and Global Characterization Factors (CF) for Habitat Loss Due to Transmission and Distribution Lines

	Mammals				Birds			
Country code	Regional CF [PDF*y/kWh]		Global CF [PDF*y/kWh * GEP]		Regional CF [PDF*y/kWh]		Global CF [PDF*y/kWh * GEP]	
	Transmission	Distribution	Transmission	Distribution	Transmission	Distribution	Transmission	Distribution
AGO	2.01726E-15	1.97428E-14	1.01227E-17	9.90703E-17	1.96733E-15	1.92542E-14	9.87212E-18	9.66180E-17
ALB	1.92917E-14	1.48129E-14	3.18633E-18	2.44658E-18	1.97466E-14	1.51621E-14	3.26146E-18	2.50426E-18
ARE	5.91417E-18	3.97744E-18	7.94068E-22	5.34032E-22	5.59947E-18	3.76580E-18	7.51815E-22	5.05616E-22
ARG	1.29718E-15	1.82554E-15	3.09722E-17	4.35877E-17	1.31634E-15	1.85250E-15	3.14296E-17	4.42314E-17
ARM	5.19721E-16	4.23700E-16	8.17701E-19	6.66627E-19	5.24425E-16	4.27536E-16	8.25102E-19	6.72662E-19
AUS	1.40812E-15	7.08435E-16	5.64062E-17	2.83783E-17	1.41510E-15	7.10239E-16	5.66856E-17	2.84506E-17
AUT	1.36891E-15	8.11828E-16	1.13889E-18	6.75413E-19	1.47084E-15	8.72267E-16	1.22369E-18	7.25696E-19
AZE	1.33070E-16	2.76447E-15	1.07074E-19	2.22441E-18	1.31136E-16	2.72429E-15	1.05518E-19	2.19208E-18
BEL	1.52166E-16	1.26605E-16	3.54115E-21	2.94632E-21	1.59059E-16	1.32341E-16	3.70157E-21	3.07978E-21
BEN	4.86816E-15	8.07694E-15	2.53447E-18	4.20503E-18	4.71342E-15	7.82017E-15	2.45391E-18	4.07135E-18
BGD	1.23421E-15	3.26964E-15	7.27879E-19	1.92828E-18	1.27610E-15	3.38064E-15	7.52586E-19	1.99375E-18
BGR	3.31244E-15	4.58284E-15	1.61602E-18	2.23580E-18	3.44697E-15	4.76896E-15	1.68165E-18	2.32660E-18
BHR	-	7.23725E-19	-	6.65472E-26	-	6.98213E-19	-	6.42014E-26
BIH	9.30761E-15	1.12461E-14	2.01256E-18	2.43171E-18	1.00400E-14	1.21309E-14	2.17092E-18	2.62304E-18
BLR	1.05312E-15	4.14763E-16	1.91280E-19	7.53338E-20	1.14781E-15	4.52052E-16	2.08478E-19	8.21067E-20
BOL	4.63581E-15	2.48827E-14	5.27772E-17	2.83282E-16	4.67090E-15	2.50711E-14	5.31767E-17	2.85426E-16
BRA	3.90245E-15	5.31409E-15	2.58183E-16	3.51577E-16	3.89760E-15	5.30756E-15	2.57863E-16	3.51145E-16
BRN	5.64378E-16	3.55296E-15	1.57431E-19	9.91082E-19	5.63115E-16	3.54501E-15	1.57078E-19	9.88864E-19
BWA	1.45112E-14	2.50159E-14	2.04135E-17	3.51910E-17	1.42941E-14	2.46417E-14	2.01081E-17	3.46645E-17
CAN	5.71830E-16	3.67303E-16	2.99991E-18	1.92693E-18	7.00439E-16	4.53149E-16	3.67461E-18	2.37729E-18
CHE	1.00580E-15	2.56463E-16	1.40459E-19	3.58147E-20	1.07164E-15	2.73247E-16	1.49654E-19	3.81586E-20
CHL	6.59474E-16	1.16902E-15	4.55395E-18	8.07257E-18	6.71947E-16	1.19113E-15	4.64008E-18	8.22524E-18
CHN	9.28713E-17	2.88057E-16	3.64553E-18	1.13073E-17	9.76446E-17	3.05232E-16	3.83290E-18	1.19814E-17
CIV	1.19587E-14	4.02850E-14	7.49660E-17	2.52535E-16	1.12638E-14	3.79434E-14	7.06097E-17	2.37856E-16
CMR	3.63014E-15	8.37755E-14	4.99934E-17	1.15373E-15	3.46034E-15	7.99251E-14	4.76549E-17	1.10071E-15
COD	1.48273E-15	4.65288E-14	3.68556E-17	1.15654E-15	1.44299E-15	4.45707E-14	3.58678E-17	1.10787E-15
COG	1.20756E-15	5.70310E-14	4.41573E-18	2.08546E-16	1.15439E-15	5.44257E-14	4.22128E-18	1.99020E-16
COL	5.55323E-15	2.88942E-14	1.32581E-16	6.89835E-16	5.53984E-15	2.88205E-14	1.32261E-16	6.88076E-16
CRI	2.02442E-14	6.42583E-14	5.14324E-17	1.63254E-16	2.02026E-14	6.41261E-14	5.13266E-17	1.62918E-16
CUB	2.51946E-14	7.72125E-14	8.86685E-17	2.71738E-16	2.51077E-14	7.69461E-14	8.83627E-17	2.70800E-16
CYP	1.57911E-14	3.37221E-14	3.27742E-18	6.99899E-18	1.67403E-14	3.57494E-14	3.47443E-18	7.41975E-18
CZE	2.52477E-16	2.52006E-16	2.34319E-20	2.33881E-20	2.72150E-16	2.71641E-16	2.52577E-20	2.52105E-20
DEU	2.20836E-16	1.73440E-16	7.07188E-20	5.55413E-20	2.32566E-16	1.82653E-16	7.44753E-20	5.84914E-20
DNK	3.18292E-16	2.40566E-16	6.73989E-20	5.09402E-20	3.32573E-16	2.51359E-16	7.04230E-20	5.32259E-20
DOM	4.39359E-15	4.76309E-14	4.09633E-18	4.44083E-17	4.37760E-15	4.74230E-14	4.08142E-18	4.42145E-17
DZA	1.57164E-16	3.97322E-16	3.27619E-19	8.28247E-19	1.47182E-16	3.71565E-16	3.06811E-19	7.74554E-19
ECU	1.10039E-14	5.82602E-14	1.53326E-16	8.11784E-16	1.09996E-14	5.82375E-14	1.53266E-16	8.11467E-16
EGY	1.21370E-17	8.08500E-18	1.73402E-20	1.15511E-20	1.11284E-17	7.42994E-18	1.58992E-20	1.06152E-20
ERI	1.75557E-16	7.00534E-15	8.22300E-20	3.28127E-18	1.65730E-16	6.61318E-15	7.76270E-20	3.09758E-18
ESP	4.55076E-15	3.22140E-15	1.52751E-17	1.08130E-17	4.59185E-15	3.25046E-15	1.54130E-17	1.09105E-17
EST	2.13818E-15	4.19964E-16	5.16611E-20	1.01469E-20	2.34062E-15	4.59722E-16	5.65524E-20	1.11075E-20
ETH	4.02726E-15	1.67087E-14	5.91398E-17	2.45366E-16	3.79139E-15	1.57325E-14	5.56762E-17	2.31030E-16
FIN	4.04601E-16	1.43964E-16	4.01608E-20	1.42899E-20	4.40649E-16	1.56789E-16	4.37389E-20	1.55629E-20
FRA	1.19174E-15	8.00775E-16	6.32889E-18	4.25263E-18	1.22161E-15	8.20843E-16	6.48753E-18	4.35921E-18

Country code	Mammals: Regional CF [PDF*y/kWh] Transmission	Mammals: Regional CF [PDF*y/kWh] Distribution	Mammals: Global CF [PDF*y/kWh * GEP] Transmission	Mammals: Global CF [PDF*y/kWh * GEP] Distribution	Birds: Regional CF [PDF*y/kWh] Transmission	Birds: Regional CF [PDF*y/kWh] Distribution	Birds: Global CF [PDF*y/kWh * GEP] Transmission	Birds: Global CF [PDF*y/kWh * GEP] Distribution
GAB	5.12845E-15	5.27859E-14	1.58081E-17	1.62709E-16	4.87710E-15	5.01985E-14	1.50333E-17	1.54733E-16
GBR	2.75747E-16	2.07823E-16	4.29058E-20	3.23368E-20	2.87549E-16	2.16717E-16	4.47421E-20	3.37207E-20
GEO	5.05177E-15	5.36126E-15	4.71807E-18	5.00711E-18	5.10649E-15	5.41933E-15	4.76918E-18	5.06134E-18
GHA	2.37586E-15	1.62888E-14	8.06844E-18	5.53168E-17	2.24319E-15	1.53789E-14	7.61788E-18	5.22269E-17
GIB	-	-	-	-	-	-	-	-
GNQ	3.18848E-14	6.17165E-14	7.96071E-17	1.54089E-16	3.03623E-14	5.93990E-14	7.58059E-17	1.48302E-16
GRC	8.17264E-15	1.14636E-14	9.12990E-18	1.28064E-17	7.92407E-15	1.11149E-14	8.85222E-18	1.24168E-17
GTM	9.78706E-15	7.66094E-14	4.10834E-17	3.21585E-16	9.76020E-15	7.63991E-14	4.09706E-17	3.20702E-16
GUY	-	2.26929E-14	-	3.40633E-17	-	2.26250E-14	-	3.39614E-17
HND	2.79073E-15	9.16849E-14	6.28614E-18	2.06521E-16	2.78336E-15	9.14371E-14	6.26955E-18	2.05963E-16
HRV	1.30996E-14	6.31028E-15	1.98459E-18	9.56008E-19	1.39928E-14	6.74054E-15	2.11991E-18	1.02119E-18
HTI	6.88889E-15	4.98999E-13	2.16801E-18	1.57040E-16	6.86371E-15	4.96890E-13	2.16008E-18	1.56377E-16
HUN	5.37685E-16	2.42396E-16	2.23813E-19	1.00898E-19	6.10251E-16	2.75108E-16	2.54019E-19	1.14515E-19
IDN	2.30953E-15	2.44733E-14	2.08513E-16	2.20954E-15	2.30107E-15	2.43623E-14	2.07750E-16	2.19953E-15
IND	9.51570E-16	2.05116E-15	2.55139E-17	5.49965E-17	1.01291E-15	2.17878E-15	2.71586E-17	5.84182E-17
IRL	1.73894E-16	1.31020E-16	3.27193E-21	2.46522E-21	1.83197E-16	1.38029E-16	3.44697E-21	2.59711E-21
IRN	7.79116E-17	2.48045E-16	3.95339E-19	1.25863E-18	7.68225E-17	2.44953E-16	3.89813E-19	1.24294E-18
IRQ	5.61346E-18	2.40310E-16	4.54030E-21	1.94368E-19	5.34033E-18	2.28617E-16	4.31938E-21	1.84911E-19
ISL	1.44073E-17	1.12134E-17	2.09272E-22	1.62879E-22	1.45012E-17	1.12865E-17	2.10636E-22	1.63940E-22
ISR	7.91573E-18	4.71852E-17	6.18674E-21	3.68788E-20	7.57336E-18	4.51443E-17	5.91916E-21	3.52837E-20
ITA	6.94075E-15	2.97003E-15	1.08525E-17	4.64390E-18	7.16967E-15	3.06799E-15	1.12104E-17	4.79707E-18
JAM	1.30383E-13	4.50895E-13	2.83291E-16	9.79685E-16	1.29885E-13	4.49170E-13	2.82208E-16	9.75937E-16
JOR	4.36263E-17	4.52914E-17	4.42628E-21	4.59522E-21	4.11367E-17	4.27067E-17	4.17368E-21	4.33298E-21
JPN	3.50748E-15	1.62471E-15	3.15533E-17	1.46159E-17	3.59405E-15	1.66479E-15	3.23321E-17	1.49765E-17
KAZ	1.89464E-17	3.43745E-17	8.76725E-20	1.59064E-19	2.06414E-17	3.77920E-17	9.55157E-20	1.74878E-19
KEN	5.67023E-15	1.46206E-14	6.15564E-17	1.58723E-16	5.37517E-15	1.38806E-14	5.83532E-17	1.50689E-16
KGZ	1.76751E-17	3.07609E-16	1.21820E-20	2.12009E-19	2.01827E-17	3.49802E-16	1.39102E-20	2.41088E-19
KHM	2.49316E-15	2.44607E-14	8.08696E-18	7.93421E-17	2.44595E-15	2.39975E-14	7.93384E-18	7.78397E-17
KOR	1.07936E-15	1.24097E-15	3.42015E-19	3.93226E-19	1.20157E-15	1.38147E-15	3.80741E-19	4.37744E-19
KWT	3.29804E-19	4.31141E-18	2.56449E-24	3.35246E-23	3.18142E-19	4.15894E-18	2.47380E-24	3.23391E-23
LAO	7.49761E-15	5.62200E-14	5.67992E-17	4.25903E-16	7.40162E-15	5.55002E-14	5.60720E-17	4.20450E-16
LBN	1.95999E-16	1.10560E-15	6.16558E-21	3.47790E-20	1.90530E-16	1.07474E-15	5.99354E-21	3.38084E-20
LBY	1.37780E-17	3.04055E-17	1.74894E-20	3.85960E-20	1.28335E-17	2.83114E-17	1.62905E-20	3.59377E-20
LKA	2.30299E-14	1.08442E-13	1.65084E-16	7.77339E-16	2.34359E-14	1.10355E-13	1.67994E-16	7.91051E-16
LTU	2.69123E-15	1.30226E-16	1.11216E-19	5.38162E-21	2.93767E-15	1.42150E-16	1.21400E-19	5.87437E-21
LUX	1.60902E-15	1.47499E-16	4.00954E-21	3.67555E-22	1.70236E-15	1.56055E-16	4.24214E-21	3.88876E-22
LVA	1.71590E-15	7.19478E-16	6.20586E-20	2.60213E-20	1.87836E-15	7.87590E-16	6.79343E-20	2.84847E-20
MAR	1.46392E-15	4.95453E-15	3.32655E-18	1.12585E-17	1.38224E-15	4.67516E-15	3.14094E-18	1.06236E-17
MDA	1.50804E-16	4.53207E-17	1.26768E-20	3.80972E-21	1.67125E-16	5.02253E-17	1.40488E-20	4.22202E-21
MEX	9.62053E-15	3.05265E-14	4.68129E-16	1.48540E-15	9.67546E-15	3.06935E-14	4.70803E-16	1.49353E-15
MKD	4.59587E-15	6.27950E-15	6.48166E-19	8.85612E-19	4.73347E-15	6.46751E-15	6.67571E-19	9.12126E-19
MLT	-	-	-	-	-	-	-	-
MMR	3.69799E-15	4.08823E-14	3.27725E-17	3.62309E-16	3.66737E-15	4.07012E-14	3.25011E-17	3.60703E-16
MNE	2.05942E-14	1.26593E-14	1.78352E-18	1.09633E-18	2.19604E-14	1.34990E-14	1.90184E-18	1.16906E-18
MNG	1.14353E-17	1.01868E-16	3.30622E-20	2.94525E-19	1.20605E-17	1.07123E-16	3.48698E-20	3.09720E-19

Country code	Mammals				Birds			
	Regional CF [PDF*y/kWh]		Global CF [PDF*y/kWh * GEP]		Regional CF [PDF*y/kWh]		Global CF [PDF*y/kWh * GEP]	
	Transmission	Distribution	Transmission	Distribution	Transmission	Distribution	Transmission	Distribution
MOZ	1.22424E-14	1.86202E-14	4.38234E-17	6.66537E-17	1.18077E-14	1.79591E-14	4.22675E-17	6.42871E-17
MUS	-	-	-	-	-	-	-	-
MYS	6.37975E-15	1.39294E-14	1.09223E-16	2.38475E-16	6.34462E-15	1.38527E-14	1.08622E-16	2.37162E-16
NAM	1.18673E-13	2.81753E-14	3.44653E-16	8.18276E-17	1.14786E-13	2.72526E-14	3.33366E-16	7.91477E-17
NER	1.09603E-17	3.84175E-16	1.44513E-20	5.06540E-19	1.03924E-17	3.60853E-16	1.37026E-20	4.75789E-19
NGA	5.63478E-15	2.17385E-14	3.74608E-17	1.44521E-16	5.37351E-15	2.07041E-14	3.57238E-17	1.37643E-16
NIC	5.40600E-15	6.18980E-14	9.53276E-18	1.09149E-16	5.39419E-15	6.17493E-14	9.51194E-18	1.08887E-16
NLD	4.40009E-17	5.20875E-17	1.05613E-21	1.25023E-21	4.58375E-17	5.42615E-17	1.10021E-21	1.30241E-21
NOR	1.98273E-15	8.82538E-16	2.95995E-19	1.31751E-19	2.26336E-15	1.00744E-15	3.37889E-19	1.50397E-19
NPL	1.87105E-14	4.36966E-14	4.23090E-17	9.88084E-17	1.97444E-14	4.60722E-14	4.46467E-17	1.04180E-16
NZL	5.11729E-15	3.43673E-15	8.88380E-18	5.96629E-18	4.84737E-15	3.25546E-15	8.41522E-18	5.65160E-18
OMN	2.23614E-17	1.29944E-16	2.35993E-20	1.37138E-19	2.06888E-17	1.20224E-16	2.18340E-20	1.26880E-19
PAK	4.73613E-16	1.40218E-15	8.82992E-19	2.61418E-18	5.08800E-16	1.50460E-15	9.48594E-19	2.80514E-18
PAN	1.49187E-14	5.08429E-14	5.74159E-17	1.95673E-16	1.48867E-14	5.07430E-14	5.72925E-17	1.95288E-16
PER	9.76680E-16	1.13500E-14	2.19205E-17	2.54738E-16	9.77365E-16	1.13584E-14	2.19359E-17	2.54927E-16
PHL	7.71630E-15	2.28245E-14	1.70471E-16	5.04247E-16	7.64737E-15	2.26060E-14	1.68948E-16	4.99419E-16
POL	6.75884E-16	6.00409E-16	1.81432E-19	1.61171E-19	7.22313E-16	6.41651E-16	1.93895E-19	1.72242E-19
PRK	1.87933E-15	4.19066E-15	1.07651E-18	2.40047E-18	2.07176E-15	4.61980E-15	1.18674E-18	2.64630E-18
PRT	7.48369E-15	6.70254E-15	4.50763E-18	4.03712E-18	7.63885E-15	6.84147E-15	4.60109E-18	4.12080E-18
PRY	3.20256E-16	4.70070E-15	6.91596E-19	1.01512E-17	3.21477E-16	4.71861E-15	6.94232E-19	1.01899E-17
QAT	-	1.94091E-19	-	7.69602E-25	-	1.86857E-19	-	7.40917E-25
ROU	1.15302E-15	1.66372E-15	2.42995E-18	3.50624E-18	1.25843E-15	1.81583E-15	2.65211E-18	3.82680E-18
RUS	5.66380E-16	4.22554E-16	6.52378E-18	4.86713E-18	6.16311E-16	4.61197E-16	7.09889E-18	5.31224E-18
SAU	5.07342E-18	2.51451E-17	7.04041E-21	3.48939E-20	4.66804E-18	2.31359E-17	6.47787E-21	3.21058E-20
SDN	5.23839E-17	5.25465E-16	1.38576E-19	1.39006E-18	4.98452E-17	4.98172E-16	1.31860E-19	1.31786E-18
SEN	9.85425E-17	1.35750E-15	6.00507E-20	8.27247E-19	9.41785E-17	1.29738E-15	5.73914E-20	7.90610E-19
SGP	-	1.05011E-17	-	1.13973E-21	-	1.04356E-17	-	1.13261E-21
SLV	7.20979E-15	2.15385E-14	2.61026E-18	7.79787E-18	7.18846E-15	2.14748E-14	2.60254E-18	7.77480E-18
SRB	1.73215E-15	2.86368E-15	3.71370E-19	6.13968E-19	1.84093E-15	3.04351E-15	3.94692E-19	6.52525E-19
SUR	3.59433E-15	3.74616E-14	2.80905E-18	2.92772E-17	3.58206E-15	3.73336E-14	2.79947E-18	2.91771E-17
SVK	1.50255E-15	7.56352E-16	1.98153E-19	9.97459E-20	1.66216E-15	8.36692E-16	2.19202E-19	1.10341E-19
SVN	3.38081E-15	3.25588E-15	1.57049E-19	1.51246E-19	3.65408E-15	3.51904E-15	1.69743E-19	1.63470E-19
SWE	6.29157E-16	3.11104E-16	8.33783E-20	4.12287E-20	6.86751E-16	3.39581E-16	9.10108E-20	4.50026E-20
SYR	2.59027E-16	1.93657E-15	1.78554E-19	1.33493E-18	2.45566E-16	1.83593E-15	1.69275E-19	1.26556E-18
TGO	5.43186E-15	1.23496E-14	2.38607E-18	5.42486E-18	5.18947E-15	1.17983E-14	2.27960E-18	5.18270E-18
THA	2.73477E-15	7.21704E-15	2.13526E-17	5.63493E-17	2.69568E-15	7.11387E-15	2.10474E-17	5.55438E-17
TJK	5.25118E-18	5.31650E-17	2.22558E-21	2.25326E-20	5.69714E-18	5.77613E-17	2.41459E-21	2.44806E-20
TKM	2.28903E-16	1.86980E-16	1.82124E-19	1.48769E-19	2.35364E-16	1.90336E-16	1.87265E-19	1.51439E-19
TTO	-	2.01781E-14	-	4.29177E-18	-	2.01284E-14	-	4.28120E-18
TUN	2.79474E-16	1.02420E-15	1.52793E-19	5.59945E-19	2.62932E-16	9.58498E-16	1.43750E-19	5.24027E-19
TUR	2.04089E-15	4.87982E-15	5.87223E-18	1.40407E-17	2.07123E-15	4.95235E-15	5.95953E-18	1.42494E-17
TZA	7.66163E-15	4.43389E-14	1.19603E-16	6.92161E-16	7.26675E-15	4.21469E-14	1.13439E-16	6.57942E-16
UKR	5.46860E-16	1.75656E-16	1.05438E-18	3.38675E-19	6.03116E-16	1.93725E-16	1.16284E-18	3.73513E-19
URY	1.04653E-16	1.23512E-16	1.43904E-19	1.69836E-19	1.04904E-16	1.23809E-16	1.44249E-19	1.70244E-19
USA	1.49435E-15	1.22153E-15	4.27738E-17	3.49646E-17	1.71510E-15	1.40109E-15	4.90923E-17	4.01043E-17

Country code	Mammals				Birds			
	Regional CF [PDF*y/kWh]		Global CF [PDF*y/kWh * GEP]		Regional CF [PDF*y/kWh]		Global CF [PDF*y/kWh * GEP]	
	Transmission	Distribution	Transmission	Distribution	Transmission	Distribution	Transmission	Distribution
UZB	5.91387E-18	1.08369E-17	4.31975E-21	7.91573E-21	6.27948E-18	1.15068E-17	4.58681E-21	8.40509E-21
VEN	5.29675E-15	1.52019E-14	7.08217E-17	2.03261E-16	5.28288E-15	1.51628E-14	7.06362E-17	2.02738E-16
VNM	2.83027E-15	6.95024E-15	3.59920E-17	8.83849E-17	2.78544E-15	6.84014E-15	3.54219E-17	8.69848E-17
YEM	1.05503E-15	9.72360E-15	1.48139E-18	1.36531E-17	9.55352E-16	8.80489E-15	1.34143E-18	1.23631E-17
ZAF	1.69848E-15	2.82045E-15	2.17474E-17	3.61133E-17	1.73363E-15	2.87882E-15	2.21975E-17	3.68607E-17
ZMB	1.22120E-14	1.39121E-14	5.05106E-17	5.75423E-17	1.16465E-14	1.32678E-14	4.81714E-17	5.48774E-17
ZWE	1.10637E-14	1.71399E-14	2.11215E-17	3.27213E-17	1.07849E-14	1.67079E-14	2.05892E-17	3.18966E-17

5.

BIODIVERSITY IMPACTS OF NORWAY'S RENEWABLE ELECTRICITY GRID

In review. The Journal of Cleaner Production.

This paper is awaiting publicatin and is not included in NTNU Open

6.
DISCUSSION AND CONCLUSION

6.1 Scientific relevance and contribution

There is an urgent need to triple global renewable energy production capacity by 2030 to stay within the boundaries of 1.5 degrees Celsius global warming (COP28, IRENA & GRA, 2023). Norway is aiming to produce an additional 47 terawatt-hours (TWh) and 70 TWh from hydropower, onshore and offshore wind power, and solar power by 2040 (NVE, 2023a) and 2050 (Statnett, 2023b), respectively. This aims to facilitate extensive electrification across various sectors and to reduce emissions (KMD, 2021; NOU 2023:3, 2023).

Given that power lines are the backbone of every energy system infrastructure, modernising and expanding the global electric grid is inevitable (IEA, 2023b, 2023a). This necessity also extends to Norway (NOU 2022:6, 2022; Statnett, 2023c, 2023a).

LCA can play an important role in designing strategies for the energy system decarbonisation (Hellweg et al., 2023), and the integration of biodiversity models can help decision-makers to promote a sustainable energy transition (Luderer et al., 2019). However, recently developed biodiversity LCIA models focus solely on impacts associated with energy production from hydropower and onshore wind power plants (Dorber et al., 2020a; Dorber et al., 2019; Dorber et al., 2020b; May et al., 2020, 2021).

This thesis contributes to the LCIA framework by introducing models that quantify the main impacts of power lines on biodiversity (Chapters 2-4). Furthermore, the integration of biodiversity LCIA models of electricity production and transmission (Chapter 5) offers a baseline assessment of the current biodiversity impacts of the Norwegian electricity system. The developed characterisation factors in all the chapters can be used to quantify biodiversity impacts in the unit of the potentially disappeared fraction of species (PDF), the recommended metric to evaluate the damage to ecosystem quality (Verones et al., 2017).

New biodiversity LCIA models quantifying the impacts of power lines

This thesis introduces the first biodiversity LCIA models to quantify the impacts of power lines on two taxonomic groups: birds and mammals (Chapters 2-4). These animal taxa have been extensively studied regarding power line effects on biodiversity (Biasotto & Kindel, 2018; Richardson et al., 2017). The models of collision and electrocution were newly developed to address the primary impacts of power lines on bird richness (Chapter 2). In contrast, the habitat conversion and fragmentation model is an adapted version of existing LCIA global models (Kuipers et al., 2021a; 2021b), applied to quantify the effects of power lines on bird and mammal richness (Chapter 3). All the models are spatially explicit, utilising data on the location of transmission and distribution lines and their associated pylons and species presence probabilities.

Consequently, this methodology can identify power line sections or areas that pose a higher risk for bird and mammal diversity (see Figure 6.1). Furthermore, given that collision and electrocution affect species differently based on species-specific characteristics (Bernardino et al., 2018; Bevanger, 1998), PDF maps are initially computed per species group before aggregation into taxa. This approach allows for the identification of hazardous areas for vulnerable species groups.

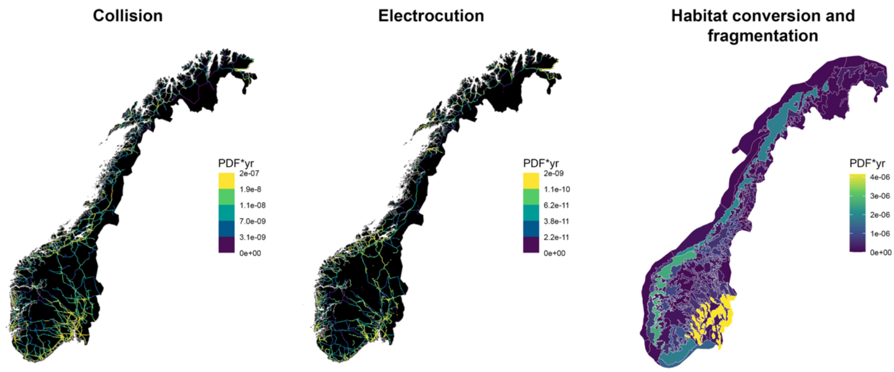


Figure 6.1. The impacts of transmission lines are quantified in units of the potentially disappeared fraction of species (PDF * yr), highlighting regions with higher impacts (brighter colours) on bird richness. All the impact pathways are conducted at a pixel level. The habitat conversion and fragmentation model (right) undergoes further aggregation to larger spatial units (i.e., landscape regions) to align with the original habitat loss and fragmentation models developed by Kuipers et al. (2021a; 2021b). Source: Chapters 2 and 3.

All three models operate at the pixel level, facilitating a detailed regional analysis. This is crucial when aiming to address the impacts of the Norwegian electricity system, as region-based models offer a higher accuracy over global models (Mutel et al., 2019).

Characterisation factors may have various spatial levels, ranging from the original regional level to an averaged level based on country, continent, or global units. These characterisation factors must be linked with the life cycle inventory data to be implemented into LCA applications (Verones et al., 2020).

In Chapters 2-3, the characterisation factors demonstrate how the impacts of Norway's electricity grid can be quantified at a regional level. Chapter 4 serves as an example of the potential of these models to achieve global coverage. By feeding the models with accessible input data, such as the global grid network (Arderne et al., 2020) and land cover map (Buchhorn et al., 2020), assessing the effects of power lines on a global scale becomes feasible. This is especially true for the habitat conversion and fragmentation model, which is adapted from global models (Kuipers et al., 2021a; 2021b). While the collision and electrocution models require supplementary bird data (i.e., body measurements), they could also be transformed into global models.

The current biodiversity impacts of the Norwegian electricity system

Chapter 5 quantified the biodiversity impacts of today's Norwegian electricity system. This is the first analysis to incorporate various biodiversity LCIA models, enabling a system-wide evaluation of the overall effects of electricity production and transmission on species richness in Norway. The findings in this chapter present the current pressure of the electricity system on Norwegian biodiversity. Notably, the final characterisation factors were computed at the regional pricing area level, illustrating how geographically uneven electricity generation and consumption are across the country. However, the initial modelling was conducted at the individual power plant level, highlighting facilities with a more evident impact (see Figure 6.2).

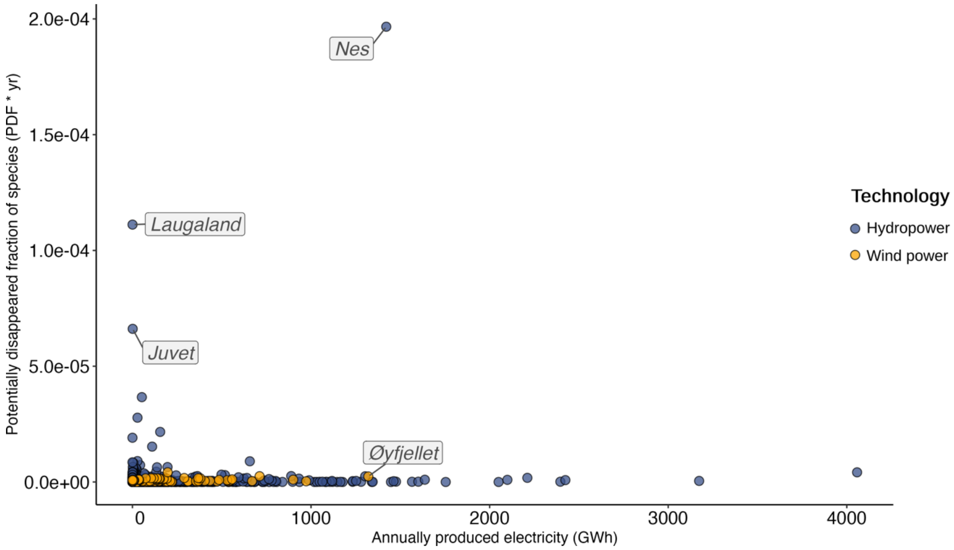


Figure 6.2. The potentially disappeared fraction of species (PDF * yr) caused by individual Norwegian hydropower plants (blue circles) and onshore wind power plants (orange circles) and their annual electricity production (Gigawatt-hours; GWh). Source: data from Chapter 5.

The further development of energy infrastructure aims to enhance Norway's electricity production capacity over the coming decades (NOU 2023:3, 2023; NVE, 2023a; Statnett, 2023b). Yet its effect on biodiversity remains unknown. Chapter 5 offers a methodology to assess the potential impacts on species richness from constructing new power lines, onshore wind power and hydropower facilities. Furthermore, integrating new biodiversity LCIA models, focusing on offshore wind (Zhou et al., 2022) and solar power, can expand the scope of the analysis for Norway's future electricity system. Therefore, Chapter 5 serves as a stepping stone for developing future energy scenarios, highlighting which planned power plants and power lines are most efficient (i.e., PDF * yr /GWh produced or transmitted) or have a high and low impact on biodiversity.

6.2 Limitations and uncertainties

Uncertainty is an integral aspect of LCIA. It is not to be ignored but presented transparently, as reporting uncertainties can enhance the results of an LCA study by highlighting its robustness (Rosenbaum et al., 2018; Verones et al., 2017). Since this thesis focuses on developing and adapting LCIA models, it is associated with parameter and model uncertainty. Parameter uncertainty refers to inaccurate, deficient, or inadequate input data in the model. Model uncertainty, on the other hand, is derived from the structure of the model itself. For example, a simplistic model demanding minimal input data may inadequately capture environmental impacts, exhibiting low parameter uncertainty but high model uncertainty. A complex model requiring a wide range of parameters may better portray how certain impacts affect the environment, reflecting low model uncertainty but high parameter uncertainty (Rosenbaum et al., 2018).

Parameter uncertainty

As all the models presented in this thesis are spatially explicit, the spatial data can be a source of uncertainty. A good example are the spatial datasets for Norwegian and global electricity grids. The Norwegian Water Resources and Energy Directorate (Noregs vassdrags- og energidirektorat; NVE) compiled the Norwegian dataset (NVE, 2024a) that appeared in Chapters 2, 3 and 5. The global dataset was modelled by Arderne et al. (2020) and applied in Chapter 4. As illustrated in Figure 6.3, although both datasets cover Norway, they provide a different spatial scale quality.

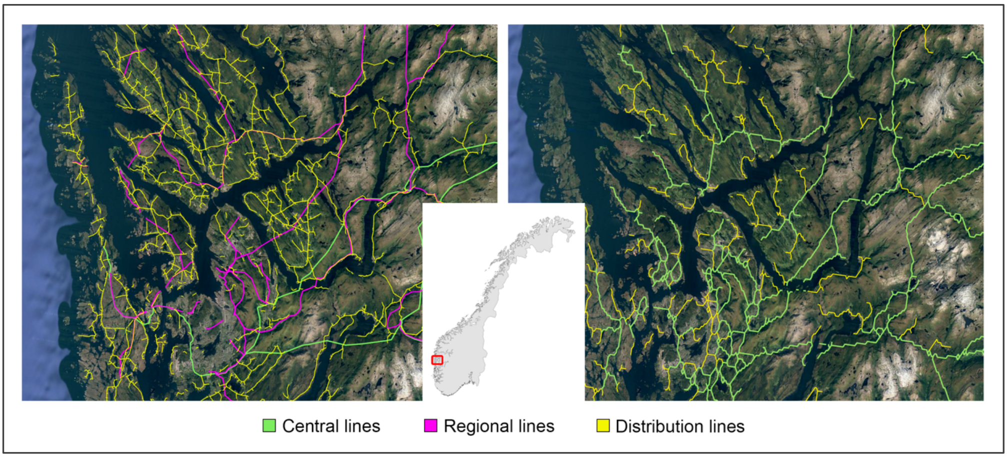


Figure 6.3. A comparison between the coverage of the Norwegian (left) and the global (right) grid network datasets in southwest Norway. The red rectangle on Norway's map indicates the location of the two images. Sources: Arderne et al. (2020); Google Maps (2024); NVE (2023b).

The Norwegian data are categorised into the three power line types (NOU 2022:6, 2022), while the global dataset comprises a coarser classification of just transmission and distribution lines.

Moreover, the local NVE dataset has better coverage compared to the global grid network, which has gaps and missing sections.

Nevertheless, as national (i.e., Statnett), regional and local grid companies manage the Norwegian grid system rather than NVE itself, this can also lead to inaccuracies in their datasets. For instance, the NVE pylon dataset has not undergone systematic updates since its creation in 2009 (C. Kvamme, NVE, personal communication, June 10, 2021) and contains duplicated records. Despite these limitations, both datasets offer a valuable portrayal of the electric networks they aim to represent.

The width of the rights-of-way is a crucial factor in each of the power lines models: collision, electrocution, habitat loss, and habitat conversion and fragmentation (Chapters 2-5). It serves as a source for potential overestimation and underestimation of the impacts. While the width of the power line corridors depends on the type of the power line and its voltage capacity, the width of the Norwegian rights-of-way may also vary based on environmental characteristics such as vegetation type (i.e., coniferous or deciduous trees), soil conditions, and topography (NVE, 2016). In Chapter 4, width measurements for transmission and distribution lines rely on a range recommended by the International Finance Corporation of the World Bank Group (IFC, 2007): 15-30 m for transmission lines and 12-24 m for distribution lines. Consequently, a high degree of uncertainty exists in the global LCIA models due to the generalised nature of rights-of-way widths. Chapters 2, 3 and 5 aim to minimise this uncertainty by classifying power line corridors based on their voltage level rather than treating all as a single category (i.e., transmission or distribution lines). Widths were assigned by the voltage capacity of the power lines: 40 metres (m) for lines carrying 420 kilovolts (kV), 35 m for 420-300 kV, 25-30 m for 300-132 kV, and 20 m for lines under 132 kV. Although the estimates for widths of 420 – 132 kV lines may vary due to factors such as the age of the lines and pre-construction agreements, these dimensions were provided by Statnett (A. Granheim, Statnett, personal communication, June 18, 2021). According to NVE, the recommended rights-of-way width for 22 kV lines should be 15-20 m (NVE, 2016). Given that all the central lines operate above 132 kV, and most distribution lines carry 20-24 kV, higher uncertainty persists by the regional lines. The regional lines operate within the 33 – 132 kV range, with the majority falling between 50 and 110 kV. As power line corridors in Norway operating at 66 kV typically have a width ranging between 12-24 m (Bevanger & Thingstad, 1988), the assigned estimate of 20 m closely aligns with this range.

Another good example of parameter uncertainty lies in the species distribution maps utilised in Chapters 2, 3, and 5 to assess bird and mammal richness in Norway. These maps were modelled using species presence data from the Global Biodiversity Information Facilities (GBIF, 2024). Yet, they do not account for absence data, as mentioned in Chapter 3 and by May et al. (2021). Moreover, as GBIF species records can be collected by anyone, records may often originate from accessible sites (Tiago et al., 2017) and lack systematic collection methods (Isaac & Pocock, 2015). In addition, uncertainty might arise from the environmental predictors employed in generating these maps, with each predictor potentially introducing its own level of uncertainty. For example, climate variables (Braunisch et al., 2013; Stoklosa et al., 2015). Nevertheless, as the species distribution maps estimate the likelihood of species' presence across Norway, they illustrate the spatial variation in the presence of species, capturing habitat suitability at a pixel resolution of 1 km^2.

In LCIA, models often rely on large-scale species distribution maps to address the pressure on species richness (Damiani et al., 2023). This was demonstrated in Chapter 4 through range maps from IUCN and BirdLife International. However, these maps assume that species uniformly occupy their entire distribution range, thereby failing to show variations in species richness across ranges (Herkt et al., 2017; Pineda & Lobo, 2012). Therefore, although species distribution maps may have inherent uncertainties, they offer a better spatial representation of species' presence likelihood. This is particularly important given that the impacts associated with electricity production and transmission are site-specific (OECD, 2024).

Model uncertainty

The PDF is the selected metric utilised across all LCIA models presented in this thesis (Chapters 2-5). Acting as an endpoint indicator, the PDF quantifies the relative loss of species richness due to a certain stressor, such as collision or electrocution by power lines. However, as nature is complex and dynamic, biodiversity impacts cannot be evaluated by one single metric (Duelli & Obrist, 2003; Rounsevell et al., 2020). Although PDF serves as a valuable indicator, it is not the sole measure for assessing biodiversity impacts within LCIA. Other biodiversity indicators can be used, such as the plant functional diversity (de Souza et al., 2013; Scherer et al., 2020) or the mean species abundance (Wilting et al., 2017).

Currently, LCIA lacks a standardised methodology to comprehensively evaluate environmental impacts on biodiversity across various levels, including ecosystems, taxa, and essential biodiversity variable classes (e.g., genetic and community compositions, species population and traits, ecosystem structure and functionality) (Damiani et al., 2023). Given the relatively good data availability concerning species presence (Verones et al., 2017), species extinction (e.g., potentially disappeared fraction of species) stands out as an ideal metric, representing the reduction in species diversity, which is the core idea of biodiversity loss. This metric can also be communicated easily to the general public (Rounsevell et al., 2020).

The choice of PDF in the power lines models was deliberate, as it is currently the most common indicator in LCIA for assessing biodiversity impacts (Crenna et al., 2020; Damiani et al., 2023; Verones et al., 2017). Furthermore, it aligns with the existing biodiversity LCIA models in Chapter 5 (May et al., 2020, 2021; Pierrat et al., 2023), which use the same biodiversity indicator.

In LCIA, ecosystem impacts are often characterised in a generalised manner, typically quantified as the relative loss of species within a particular ecosystem (Milà i Canals & de Baan, 2015; Rosenbaum, 2015; van Zelm et al., 2015). Ecosystem impacts should cover different taxa across diverse ecosystems (i.e., freshwater and terrestrial ecosystems) before aggregating them into an overall species loss value (Verones et al., 2017). However, aggregating individual species into taxonomic groups introduces uncertainties, as unique measurements (i.e., body weight or dispersal distance) for each species are averaged across the entire group. This uncertainty is evident in the sensitivity analyses (see Figure 6.4 and the Supporting Information), where certain species groups encompass many species while others consist of few species. Among the three impact pathways of power lines, habitat conversion and fragmentation proved to be the impact pathway with the highest uncertainty. This can be explained by the significant variations in dispersal distances among and within the species subgroups.

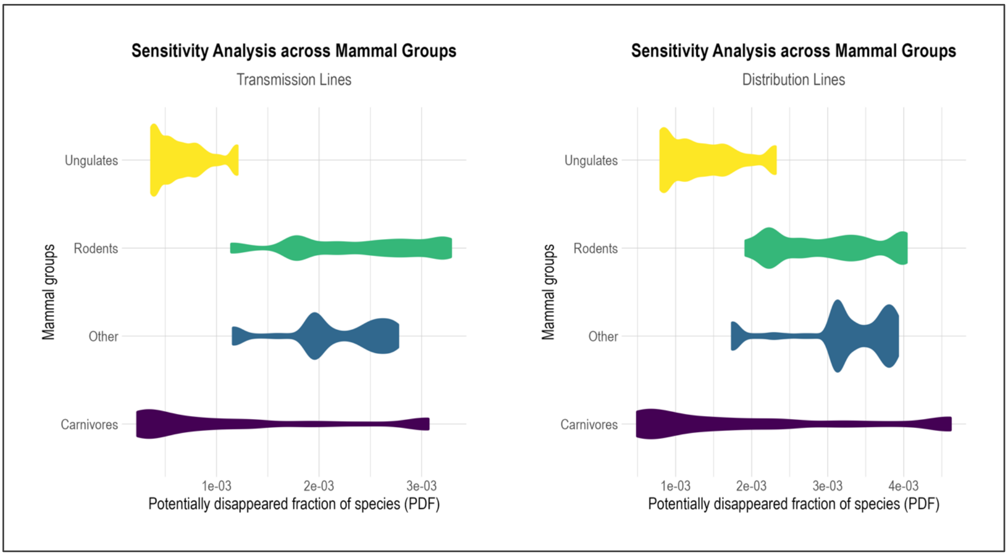


Figure 6.4. The sensitivity analysis highlights the variability of the disappeared fraction of species (PDF * yr) metric computed for the impact pathway habitat conversion and fragmentation. The variation is caused by the different dispersal distances (km) of the species group. Source: data from Chapter 3.

Chapter 5 integrated nine LCIA models to evaluate the overall biodiversity impacts of electricity production and transmission. However, each model introduced its own set of uncertainties.

Hydropower models exhibited the highest level of uncertainty, especially concerning the impact pathways of habitat loss and land inundation. Areal loss estimates from Kenawi et al. (2023) and Hedger et al. (in prep.) were utilised to assess habitat loss impact by large and small-scale hydropower plants across Norway. This approach introduced considerable uncertainty due to its generalised nature, drawing from data from only a few large-scale and small-scale hydropower plants. The assessments of habitat loss and land inundation resulting from hydropower plant or reservoir development were based on a comparative analysis of satellite imagery before and after construction (Dorber et al., 2018; Hedger et al., in prep.; Kenawi et al., 2023). The history of hydropower plant development in Norway dates back to the late 19th century, with significant constructions from the early 1950s to the late 1980s (Tellefsen et al., 2020). Although aerial photographs of Norway are available from the year 1935 (Kartverket, 2023), Dorber et al. (2018) and Kenawi et al. (2023) have encountered challenges in obtaining high-resolution satellite images preceding the construction of reservoirs or power plants. This constrained their ability to analyse Norwegian power plants built before 1950 (Kenawi et al., 2023) or reservoirs established before 1972 (Dorber et al., 2018). Consequently, achieving a comprehensive and accurate quantification of the aerial alterations caused by hydropower in Norway remains limited, leading to inherent uncertainties. Nevertheless, the sensitivity analyses show that the PDF values remained relatively consistent across all technologies (i.e., hydropower and distribution lines) or impact pathways, rarely exceeding the same order of magnitude.

Additional uncertainties in the biodiversity LCIA model quantifying power lines may stem from technical aspects of the infrastructure. Firstly, the technical design of the power lines and associated pylons significantly influences the magnitude of their impact. As discussed in Chapters 1 and 2, factors like wire diameter thickness and the number of vertical wire levels can affect collision risks (Bernardino et al., 2018), while pylon design plays a great role in mitigating the risk of electrocution (Eccleston & Harness, 2018; Lehman et al., 2007).

Secondly, various mitigation measures can be implemented on power lines and pylons to reduce their impacts on bird species, which are not covered in the LCIA models due to data unavailability. Installing wire-marking has shown a significant reduction (about 50%) in bird collisions with power lines (Bernardino et al., 2019; Pavón-Jordán et al., 2020). Moreover, insulating pylons can decrease mortality rates due to electrocution (Chevallier et al., 2015).

The quantified impacts may be underestimated or overestimated since these technical features or mitigation measures are not yet integrated into the models. However, with the availability of national data, it will become possible to refine collision and electrocution risk probability metrics.

This also applies to the LCIA models discussed in Chapter 5, as mitigation measures for wind power and hydropower plants also exist.

The power lines models did not include transmission and distribution substations. A substation is responsible for transitioning high to low voltage from transmission and distribution lines or vice versa (APLIC, 2012). Their construction can lead to habitat loss. NVE maintains a dataset containing 1,777 substations for power lines, primarily for regional lines (NVE, 2023b). However, this dataset represents the substations as point features without information regarding their area footprint. Therefore, as there is a lack of data concerning the estimation of the area used by substations in Norway (F. Johansen, NVE, personal communication, January 29, 2024), substations were excluded from the power line models. Given that biodiversity impacts in the scientific literature mainly concentrate on impacts caused by wires or pylons (Bernardino et al., 2018; Biasotto & Kindel, 2018; Manville, 2016; Richardson et al., 2017), the primary focus of this thesis was quantifying the impacts associated with these infrastructure features.

Finally, the scope of this thesis is limited to covering the biodiversity impacts on three taxa: birds, fish, and mammals. The models do not account for reptiles and amphibians, despite the availability of LCIA methodologies for assessing the effects of land inundation (Dorber et al., 2020b) and habitat conversion and fragmentation (Kuipers et al., 2021b; Scherer et al., 2023) on these taxa. Since these methods rely on global data, they were unsuitable for regional assessment in Norway due to their coarse resolution.

6.3 Conclusion and outlook

Chapters 2-4 of this thesis contribute to the LCIA framework by introducing the first methodology to quantify the loss of species richness associated with electricity transmission. Currently, LCA studies focusing on power lines do not address potential impacts on species richness. However, as the global and Norwegian electric networks continue to expand, quantifying the three primary impact pathways of power lines on species richness within LCIA is highly relevant.

The application of these models offers an instrument for identifying hazardous sections of power lines, facilitating targeted mitigation efforts. With its nationwide scope, this methodology can detect areas in Norway suitable for constructing new power lines with minimal impact on biodiversity.

Additionally, the models can aid policy-makers in designing routes for the upgrade and expansion of the Norwegian grid. Since LCA serves as a comparative tool, impacts can be computed per planned power line sections and compared with each other. This could identify the magnitude of the impacts each proposed section might introduce after construction, promoting sustainable strategic planning for the Norwegian grid network.

Lastly, these models promote a holistic assessment of energy systems, allowing the evaluation of biodiversity impacts associated with electricity production and transmission, as outlined in Chapter 5.

Further research is essential to improve the accuracy of the power line models. For instance, using empirical data on bird collisions and electrocution at a national scale in Norway could validate the results of the models.

Moreover, as previously mentioned, incorporating data on the technical features of pylons and power lines would reduce the uncertainties in the models and decrease the potential for overestimating collision and electrocution impacts. As spatial methodologies to identify hazardous pylons exist on regional scales (Eccleston et al., 2023; Hernández-Lambraño et al., 2018), a similar approach could be adopted and applied to Norway.

Furthermore, Chapter 5 introduces numerous biodiversity LCIA models and presents the first system-wide approach to evaluating the impacts of electricity production and transmission on species richness. This approach reflects the current state in Norway and can offer valuable insights for further development of the Norwegian electricity system.

As Chapters 2-5 demonstrated, LCIA can effectively quantify impacts and detect spatially explicit power plants or power line sections that significantly affect biodiversity. Since the geographic location plays an enormous role in the magnitude of impacts caused by hydropower plants (Dorber et al., 2020a; Zarfl et al., 2019), wind turbines (Bulling & Köppel, 2016; Rydell et al., 2012), and power lines (Bernardino et al., 2018; D'Amico et al., 2018), strategic planning is crucial to mitigate potential impacts on species richness (OECD, 2024).

With the anticipated growth in electricity production coming from offshore wind and solar power (NVE, 2023a; Statnett, 2023b), there is a pressing need to develop and incorporate additional biodiversity LCIA models that assess the impacts of these technologies.

Spatial data on planned energy production projects, already available from NVE (NVE, 2023b, 2024b), could serve as input data for the approach presented in Chapter 5. The data could be used to compute the potential biodiversity impacts of future power plants or power lines, assisting in developing future energy scenarios for Norway. These scenarios could shed light on how planning strategies may shape the future of Norwegian society, particularly in terms of maximising electricity production while minimising adverse effects on the country's nature.

Improvement to the methodology could involve developing species distribution maps to cover a broader range of taxonomic groups in Norway. An important group to consider is bats, as they are also vulnerable to collisions with wind turbines (Sánchez-Zapata et al., 2016) and electrocution by power lines (Tella et al., 2020).

Further research into quantifying the impacts of habitat loss caused by hydropower plants and reservoirs in Norway would be immensely valuable, as it could help reduce parameter uncertainty in the LCIA hydropower models. Additionally, developing new impact pathways, i.e., fragmentation of rivers, could contribute significantly to refining these models.

While this thesis focuses on the biodiversity impacts of electricity production and transmission, it does not cover other dimensions, such as the social perspective. However, conflicts have emerged in Norway in recent years regarding the construction of onshore wind farms (NOU 2023:3, 2023), often due to negative cultural associations. Building wind turbines in untouched natural areas can impact industries like tourism or reindeer husbandry and raise concerns about the future of Norway's natural landscapes (OED, 2020). Therefore, it is crucial to integrate social acceptance considerations when planning the future of renewable energy in Norway.

Another important aspect is highlighted in Chapter 5: Norway's electricity sector is strongly influenced by its neighbouring countries, exchanging electricity through imports and exports. The anticipated global energy transition extends beyond Norway's borders, and as European countries change and adapt their energy systems, they will impact Norway's energy system (NVE, 2022, 2023a; Statnett, 2023b).

While Chapters 2, 3, and 5 provide a quantification of biodiversity impacts relevant to Norway, they present a somewhat simplified perspective given the complexity of reality. Conducting an analysis that includes additional European countries or adopting a global approach would be beneficial in gaining a better understanding of the dynamics of energy systems and their impacts on species richness. Although a local approach offers a finer scale and potentially more accurate results, a global perspective can provide comparable findings across various regions (Verones et al., 2022). While the local impacts on Norwegian biodiversity may highlight potential species loss within the region, some species might persist in neighbouring countries. However, from a global standpoint, the disappearance of certain species, particularly endemic species, due to a stressor would represent an irreversible global loss (Verones et al., 2022).

The shift towards renewable energy is inevitable if we are to mitigate the effects of climate change. However, as modern civilisations rely on Earth's diverse ecosystems, preserving biodiversity is essential for the resilience and functionality of these ecosystems. Therefore, it is crucial to strike a balance when aiming to increase electricity production from clean, renewable sources while conserving natural habitats.

References

APLIC. (2012). *Reducing Avian Collisions with Power Lines: The State of the Art in 2012*. Edison Electric Institute and Avian Power Line Interaction Committee (APLIC). Washington, D.C.

Arderne, C., Zorn, C., Nicolas, C., & Koks, E. E. (2020). Predictive mapping of the global power system using open data. *Scientific Data*, *7*(1), Article 1. https://doi.org/10.1038/s41597-019-0347-4

Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J. F., Marques, A. T., Martins, R. C., Shaw, J. M., Silva, J. P., & Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation*, *222*, 1–13. https://doi.org/10.1016/j.biocon.2018.02.029

Bernardino, J., Martins, R. C., Bispo, R., & Moreira, F. (2019). Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: A meta-analysis and guidelines for field studies. *Journal of Environmental Management*, *252*, 109651. https://doi.org/10.1016/j.jenvman.2019.109651

Bevanger, K. (1998). Biological and conservation aspects of bird mortality caused by electricity power lines: A review. *Biological Conservation*, *86*(1), 67–76. https://doi.org/10.1016/S0006-3207(97)00176-6

Bevanger, K., & Thingstad, P. G. (1988). *Forholdet fugl-konstruksjoner for overføring av elektrisk energi—En oversikt overkunnskapsnivået* (Økoforsk utredning 1988:1). Økoforsk.

Biasotto, L. D., & Kindel, A. (2018). Power lines and impacts on biodiversity: A systematic review. *Environmental Impact Assessment Review*, *71*, 110–119. https://doi.org/10.1016/j.eiar.2018.04.010

Braunisch, V., Coppes, J., Arlettaz, R., Suchant, R., Schmid, H., & Bollmann, K. (2013). Selecting from correlated climate variables: A major source of uncertainty for predicting species distributions under climate change. *Ecography*, *36*(9), 971–983. https://doi.org/10.1111/j.1600-0587.2013.00138.x

Buchhorn, M., Smets, B., Bertels, L., Roo, B. D., Lesiv, M., Tsendbazar, N.-E., Herold, M., & Fritz, S. (2020). *Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2015: Globe* (V3.0.1) [dataset]. Zenodo. https://doi.org/10.5281/zenodo.3939038

Bulling, L., & Köppel, J. (2016). Exploring the trade-offs between wind energy and biodiversity conservation. In *Handbook on Biodiversity and Ecosystem Services in Impact Assessment* (pp. 299–320). Edward Elgar Publishing. https://doi.org/10.4337/9781783478996.00019

Chevallier, C., Hernández-Matías, A., Real, J., Vincent-Martin, N., Ravayrol, A., & Besnard, A. (2015). Retrofitting of power lines effectively reduces mortality by electrocution in large birds: An example with the endangered Bonelli's eagle. *Journal of Applied Ecology*, *52*(6), 1465–1473. https://doi.org/10.1111/1365-2664.12476

COP28, IRENA & GRA. (2023). *Tripling renewable power and doubling energy efficiency by 2030: Crucial steps towards 1.5°C*. International Renewable Energy Agency (IRENA).

Crenna, E., Marques, A., La Notte, A., & Sala, S. (2020). Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges. *Environmental Science & Technology*, *54*(16), 9715–9728. https://doi.org/10.1021/acs.est.9b05153

Damiani, M., Sinkko, T., Caldeira, C., Tosches, D., Robuchon, M., & Sala, S. (2023). Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. *Environmental Impact Assessment Review*, *101*, 107134. https://doi.org/10.1016/j.eiar.2023.107134

D'Amico, M., Catry, I., Martins, R. C., Ascensão, F., Barrientos, R., & Moreira, F. (2018). Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines. *Ambio*, *47*(6), 650–656. https://doi.org/10.1007/s13280-018-1025-z

de Souza, D. M., Flynn, D. F. B., DeClerck, F., Rosenbaum, R. K., de Melo Lisboa, H., & Koellner, T. (2013). Land use impacts on biodiversity in LCA: Proposal of characterization factors based on functional diversity. *The International Journal of Life Cycle Assessment*, *18*(6), 1231–1242. https://doi.org/10.1007/s11367-013-0578-0

Dorber, M., Arvesen, A., Gernaat, D., & Verones, F. (2020a). Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection. *Scientific Reports*, *10*(1), Article 1. https://doi.org/10.1038/s41598-020-78444-6

Dorber, M., Kuipers, K., & Verones, F. (2020b). Global characterization factors for terrestrial biodiversity impacts of future land inundation in Life Cycle Assessment. *Science of The Total Environment*, *712*, 134582. https://doi.org/10.1016/j.scitotenv.2019.134582

Dorber, M., Mattson, K. R., Sandlund, O. T., May, R., & Verones, F. (2019). Quantifying net water consumption of Norwegian hydropower reservoirs and related aquatic biodiversity impacts in Life Cycle Assessment. *Environmental Impact Assessment Review*, *76*, 36–46. https://doi.org/10.1016/j.eiar.2018.12.002

Dorber, M., May, R., & Verones, F. (2018). Modeling Net Land Occupation of Hydropower Reservoirs in Norway for Use in Life Cycle Assessment. *Environmental Science & Technology*, *52*(4), 2375–2384. https://doi.org/10.1021/acs.est.7b05125

Duelli, P., & Obrist, M. K. (2003). Biodiversity indicators: The choice of values and measures. *Agriculture, Ecosystems & Environment*, *98*(1), 87–98. https://doi.org/10.1016/S0167-8809(03)00072-0

Eccleston, D. T., & Harness, R. E. (2018). Raptor Electrocutions and Power Line Collisions. In J. H. Sarasola, J. M. Grande, & J. J. Negro (Eds.), *Birds of Prey: Biology and conservation in the XXI century* (pp. 273–302). Springer International Publishing. https://doi.org/10.1007/978-3-319-73745-4_12

GBIF: The Global Biodiversity Information Facility. (2024). *What is GBIF?* https://www.gbif.org/what-is-gbif, accessed 20.02.24

Google Maps. (2024). *Google Satellite Imagery.*

Hedger, R. D., Sandercock, B. K., Sundt-Hansen, L. E., Haakon Bakken, T., & Kenawi, M. S. (in prep.). *Comparing environmental impacts of micro, mini and small hydropower plants in Norway.*

Hellweg, S., Benetto, E., Huijbregts, M. A. J., Verones, F., & Wood, R. (2023). Life-cycle assessment to guide solutions for the triple planetary crisis. *Nature Reviews Earth & Environment*, *4*(7), Article 7. https://doi.org/10.1038/s43017-023-00449-2

Herkt, K. M. B., Skidmore, A. K., & Fahr, J. (2017). Macroecological conclusions based on IUCN expert maps: A call for caution. *Global Ecology and Biogeography*, *26*(8), 930–941. https://doi.org/10.1111/geb.12601

IEA. (2023a). *Electricity Grids and Secure Energy Transitions—Enhancing the foundations of resilient, sustainable and affordable power systems.* International Energy Agency (IEA).

IEA. (2023b). *World Energy Outlook 2023.* International Energy Agency (IEA).

IFC. (2007). *General EHS Guidelines: Electric power transmission and distribution.* International Finance Corporation (IFC) World Bank Group.

Isaac, N. J. B., & Pocock, M. J. O. (2015). Bias and information in biological records. *Biological Journal of the Linnean Society*, *115*(3), 522–531. https://doi.org/10.1111/bij.12532

Kartverket. (2023). *Satellittdata.* https://kartverket.no/api-og-data/satellittdata, accessed 21.02.24

Kenawi, M. S., Alfredsen, K., Stürzer, L. S., Sandercock, B. K., & Bakken, T. H. (2023). High-resolution mapping of land use changes in Norwegian hydropower systems. *Renewable and Sustainable Energy Reviews*, *188*, 113798. https://doi.org/10.1016/j.rser.2023.113798

KMD. (2021). *Meld. St. 13 (2020–2021)—Klimaplan for 2021–2030.* Klima- og miljødepartementet (KMD). https://www.regjeringen.no/no/dokumenter/meld.-st.-13-20202021/id2827405/

Kuipers, K. J. J., Hilbers, J. P., Garcia-Ulloa, J., Graae, B. J., May, R., Verones, F., Huijbregts, M. A. J., & Schipper, A. M. (2021a). Habitat fragmentation amplifies threats from habitat loss to mammal diversity across the world's terrestrial ecoregions. *One Earth*, *4*(10), 1505–1513. https://doi.org/10.1016/j.oneear.2021.09.005

Kuipers, K. J. J., May, R., & Verones, F. (2021b). Considering habitat conversion and fragmentation in characterisation factors for land-use impacts on vertebrate species richness. *Science of The Total Environment*, *801*, 149737. https://doi.org/10.1016/j.scitotenv.2021.149737

Lehman, R. N., Kennedy, P. L., & Savidge, J. A. (2007). The state of the art in raptor electrocution research: A global review. *Biological Conservation*, *136*(2), 159–174. https://doi.org/10.1016/j.biocon.2006.09.015

Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., Fricko, O., Hejazi, M., Humpenöder, F., Iyer, G., Mima, S., Mouratiadou, I., Pietzcker, R. C., Popp, A., van den Berg, M., van Vuuren, D., & Hertwich, E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, *10*(1), Article 1. https://doi.org/10.1038/s41467-019-13067-8

Manville, A. M. (2016). Impacts to Birds and Bats Due to Collisions and Electrocutions from Some Tall Structures in the United States: Wires, Towers, Turbines, and Solar Arrays—State of the Art in Addressing the Problems. In F. M. Angelici (Ed.), *Problematic Wildlife: A Cross-Disciplinary Approach* (pp. 415–442). Springer International Publishing. https://doi.org/10.1007/978-3-319-22246-2_20

May, R., Jackson, C. R., Middel, H., Stokke, B. G., & Verones, F. (2021). Life-cycle impacts of wind energy development on bird diversity in Norway. *Environmental Impact Assessment Review*, *90*, 106635. https://doi.org/10.1016/j.eiar.2021.106635

May, R., Middel, H., Stokke, B. G., Jackson, C., & Verones, F. (2020). Global life-cycle impacts of onshore wind-power plants on bird richness. *Environmental and Sustainability Indicators*, *8*, 100080. https://doi.org/10.1016/j.indic.2020.100080

Milà i Canals, L., & de Baan, L. (2015). Land Use. In M. Z. Hauschild & M. A. J. Huijbregts (Eds.), *Life Cycle Impact Assessment* (pp. 197–222). Springer Netherlands. https://doi.org/10.1007/978-94-017-9744-3_11

Mutel, C., Liao, X., Patouillard, L., Bare, J., Fantke, P., Frischknecht, R., Hauschild, M., Jolliet, O., de Souza, D.M., Laurent, A., Pfister, S. & Verones, F. (2019). Overview and recommendations for regionalized life cycle impact assessment. *Int J Life Cycle Assess, 24*, 856–865. https://doi.org/10.1007/s11367-018-1539-4

NOU 2022:6. (2022). *Nett i tide—Om utvikling av strømnettet*. Noregs offentlege utgreiingar (NOU). https://www.regjeringen.no/no/dokumenter/nou-2022-6/id2918464/

NOU 2023:3. (2023). *Mer av alt – raskere, Energikommisjonens rapport.* Noregs offentlege utgreiingar (NOU). https://www.regjeringen.no/no/dokumenter/nou-2023-3/id2961311/

NVE. (2016). *Skogrydding i kraftledningstraséer—Forsyningssikkerhet, miljø- og landskapshensyn* (2–2016). Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/tilsyn/nytt-fra-miljoetilsynet/ny-veileder-om-skogrydding-i-kraftledningstraseer/

NVE. (2022). *Norsk og nordisk effektbalanse fram mot 2030* (20/2022). Noregs vassdrags- og energidirektorat (NVE).

NVE. (2023a). *Langsiktig kraftmarkedsanalyse 2023: Energiomstillingen—En balansegang* (25/2023). Noregs vassdrags- og energidirektorat (NVE). https://www.nve.no/energi/analyser-og-statistikk/langsiktig-kraftmarkedsanalyse/langsiktig-kraftmarkedsanalyse-2023/

NVE. (2023b). *NVE data nedlast.* Noregs Vassdrags- Og Energidirektorat (NVE). https://nedlasting.nve.no/gis/

NVE. (2024a). *NVE Atlas 3.0.* Noregs Vassdrags- Og Energidirektorat (NVE). https://atlas.nve.no/, accessed 26.01.24

NVE. (2024b). *PlanNett.* Noregs Vassdrags- Og Energidirektorat (NVE). https://plannett.nve.no/, accessed 21.02.24

OECD. (2024). *Mainstreaming Biodiversity into Renewable Power Infrastructure.* Organisation for Economic Co-operation and Development (OECD). https://doi.org/10.1787/357ac474-en

OED. (2020). *Meld. St. 28 (2019 – 2020)—Vindkraft på land—Endringer i konsesjonsbehandlingen.* Olje- og energidepartementet (OED). https://www.regjeringen.no/no/dokumenter/meld.-st.-28-20192020/id2714775/

Pavón-Jordán, D., Stokke, B. G., Åström, J., Bevanger, K., Hamre, Ø., Torsæter, E., & May, R. (2020). Do birds respond to spiral markers on overhead wires of a high-voltage power line? Insights from a dedicated avian radar. *Global Ecology and Conservation*, *24*, e01363. https://doi.org/10.1016/j.gecco.2020.e01363

Pierrat, E., Barbarossa, V., Núñez, M., Scherer, L., Link, A., Damiani, M., Verones, F., & Dorber, M. (2023). Global water consumption impacts on riverine fish species richness in Life Cycle Assessment. *Science of The Total Environment*, *854*, 158702. https://doi.org/10.1016/j.scitotenv.2022.158702

Pineda, E., & Lobo, J. M. (2012). The performance of range maps and species distribution models representing the geographic variation of species richness at different resolutions. *Global Ecology and Biogeography*, *21*(9), 935–944. https://doi.org/10.1111/j.1466-8238.2011.00741.x

Richardson, M. L., Wilson, B. A., Aiuto, D. A. S., Crosby, J. E., Alonso, A., Dallmeier, F., & Golinski, G. K. (2017). A review of the impact of pipelines and power lines on biodiversity and strategies for mitigation. *Biodiversity and Conservation*, *26*(8), 1801–1815. https://doi.org/10.1007/s10531-017-1341-9

Rosenbaum, R. K. (2015). Ecotoxicity. In M. Z. Hauschild & M. A. J. Huijbregts (Eds.), *Life Cycle Impact Assessment* (pp. 139–162). Springer Netherlands. https://doi.org/10.1007/978-94-017-9744-3_8

Rosenbaum, R. K., Georgiadis, S., & Fantke, P. (2018). Uncertainty Management and Sensitivity Analysis. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 271–321). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_11

Rounsevell, M. D. A., Harfoot, M., Harrison, P. A., Newbold, T., Gregory, R. D., & Mace, G. M. (2020). A biodiversity target based on species extinctions. *Science*, *368*(6496), 1193–1195. https://doi.org/10.1126/science.aba6592

Rydell, J., Engström, H., Hedenström, A., Kyed Larsen, J., Pettersson, J., & Green, M. (2012). *The effect of wind power on birds and bats: A synthesis*. Naturvårdsverket.

Sánchez-Zapata, J. A., Clavero, M., Carrete, M., DeVault, T. L., Hermoso, V., Losada, M. A., Polo, M. J., Sánchez-Navarro, S., Pérez-García, J. M., Botella, F., Ibáñez, C., & Donázar, J. A. (2016). Effects of Renewable Energy Production and Infrastructure on Wildlife. In R. Mateo, B. Arroyo, & J. T. Garcia (Eds.), *Current Trends in Wildlife Research* (pp. 97–123). Springer International Publishing. https://doi.org/10.1007/978-3-319-27912-1_5

Scherer, L., Rosa, F., Sun, Z., Michelsen, O., De Laurentiis, V., Marques, A., Pfister, S., Verones, F., & Kuipers, K. J. J. (2023). Biodiversity Impact Assessment Considering Land Use Intensities and Fragmentation. *Environmental Science & Technology*, *57*(48), 19612–19623. https://doi.org/10.1021/acs.est.3c04191

Scherer, L., van Baren, S. A., & van Bodegom, P. M. (2020). Characterizing Land Use Impacts on Functional Plant Diversity for Life Cycle Assessments. *Environmental Science & Technology*, *54*(11), 6486–6495. https://doi.org/10.1021/acs.est.9b07228

Statnett. (2023a). *Analyse av transportkanaler 2023-2050*. https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/analyse-av-transportkanaler/

Statnett. (2023b). *Langsiktig markedsanalyse—Norge, Norden og Europa 2022-2050*. https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/langsiktig-markedsanalyse/

Statnett. (2023c). *Systemutviklingsplan 2023*. https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/systemutviklingsplan/

Stoklosa, J., Daly, C., Foster, S. D., Ashcroft, M. B., & Warton, D. I. (2015). A climate of uncertainty: Accounting for error in climate variables for species distribution models. *Methods in Ecology and Evolution*, *6*(4), 412–423. https://doi.org/10.1111/2041-210X.12217

Tella, J. L., Hernández-Brito, D., Blanco, G., & Hiraldo, F. (2020). Urban Sprawl, Food Subsidies and Power Lines: An Ecological Trap for Large Frugivorous Bats in Sri Lanka? *Diversity*, *12*(3), Article 3. https://doi.org/10.3390/d12030094

Tellefsen, T., van Putten, J., & Gjerde, O. (2020). Norwegian Hydropower: Connecting to Continental Europe. *IEEE Power and Energy Magazine*, *18*(5), 27–35. https://doi.org/10.1109/MPE.2020.3001417

Tiago, P., Ceia-Hasse, A., Marques, T. A., Capinha, C., & Pereira, H. M. (2017). Spatial distribution of citizen science casuistic observations for different taxonomic groups. *Scientific Reports*, *7*(1), Article 1. https://doi.org/10.1038/s41598-017-13130-8

van Zelm, R., Roy, P.-O., Hauschild, M. Z., & Huijbregts, M. A. J. (2015). Acidification. In M. Z. Hauschild & M. A. J. Huijbregts (Eds.), *Life Cycle Impact Assessment* (pp. 163–176). Springer Netherlands. https://doi.org/10.1007/978-94-017-9744-3_9

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A., Liao, X., Lindner, J. P., Maia de Souza, D., Michelsen, O., Patouillard, L., Pfister, S., Posthuma, L., Prado, V., Ridoutt, B., Rosenbaum, R. K., … Fantke, P. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. *Journal of Cleaner Production*, *161*, 957–967. https://doi.org/10.1016/j.jclepro.2017.05.206

Verones, F., Kuipers, K., Núñez, M., Rosa, F., Scherer, L., Marques, A., Michelsen, O., Barbarossa, V., Jaffe, B., Pfister, S., & Dorber, M. (2022). Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment. *Ecological Indicators*, *142*, 109204. https://doi.org/10.1016/j.ecolind.2022.109204

Wilting, H. C., Schipper, A. M., Bakkenes, M., Meijer, J. R., & Huijbregts, M. A. J. (2017). Quantifying Biodiversity Losses Due to Human Consumption: A Global-Scale Footprint Analysis. *Environmental Science & Technology*, *51*(6), 3298–3306. https://doi.org/10.1021/acs.est.6b05296

Zarfl, C., Berlekamp, J., He, F., Jähnig, S. C., Darwall, W., & Tockner, K. (2019). Future large hydropower dams impact global freshwater megafauna. *Scientific Reports*, *9*(1), Article 1. https://doi.org/10.1038/s41598-019-54980-8

Zhou, W., Hagos, D. A., Stikbakke, S., Huang, L., Cheng, X., & Onstein, E. (2022). Assessment of the impacts of different policy instruments on achieving the deep decarbonization targets of island energy systems in Norway – The case of Hinnøya. *Energy*, *246*, 123249. https://doi.org/10.1016/j.energy.2022.123249

SUPPORTING INFORMATION FOR CHAPTER 2

Between the Lines: Life Cycle Impact Assessment Models of Collision and Electrocution Impacts of Power Lines on Bird Diversity in Norway.

Between the Lines: Life Cycle Impact Assessment Models of Collision and Electrocution Impacts of Power Lines on Bird Diversity in Norway

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Supporting Information 1 (Tables S1-14)

This supporting information includes Tables S1-14. Table S1 is a dataset including all 271 bird species, including group, migratory category, body measurements, and Elton traits. Table S2 presents the values for distance phase to phase (Dpp). Tables S3-7 are tables with wing area, collision risk probability, wingspan, pylon use behavior, and the potentially disappeared fraction of species for collision and electrocution across the 13 bird groups. Table S8 is a table with the characterization factors for collision and electrocution across the five pricing areas in Norway. Table S9 is a glossary for the acronyms in the manuscript. The tables S10-14 show the results of the sensitivity analyses.

Supporting Information 1 can be retrieved at:
https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fjiec.13488&file=jiec13488-sup-0001-SuppMat.xlsx

Supporting Information 2 (Figures S1-9)

This supplementary information contains additional figures that were not included in the manuscript. Figures S1 and S2 display the aggregated maps of potentially disappeared fractions of species (PDF) for collision and electrocution impacts of transmission and distribution lines. Figures S3 and S4 present the characterization factors that quantify the impacts of electricity production and consumption on bird richness caused by collision and electrocution associated with transmission and distribution lines. Figures S5 and S6 show the results of the sensitivity analyses and illustrate the variation in the PDF values concerning the collision risk probability, pylon use behavior, and wingspan. Figures S7-9 show how these factors influence the PDF values across the bird groups.

SUPPORTING INFORMATION FOR:

Gilad, D., May, R., Stokke, B.G. & Verones, F. (2024). Between the Lines: Life Cycle Impact Assessment Models of Collision and Electrocution Impacts of Power Lines on Bird Diversity in Norway. Journal of Industrial Ecology.

Summary

This supplementary information contains additional figures that were not included in the manuscript. Figures S1 and S2 display the aggregated maps of potentially disappeared fractions of species (PDF) for collision and electrocution impacts of transmission and distribution lines. Figures S3 and S4 present the characterization factors that quantify the impacts of electricity production and consumption on bird richness caused by collision and electrocution associated with transmission and distribution lines. Figures S5 and S6 show the results of the sensitivity analyses and illustrate the variation in the PDF values concerning the collision risk probability, pylon use behavior, and wingspan. Figures S7-9 show how these factors influence the PDF values across the bird groups.

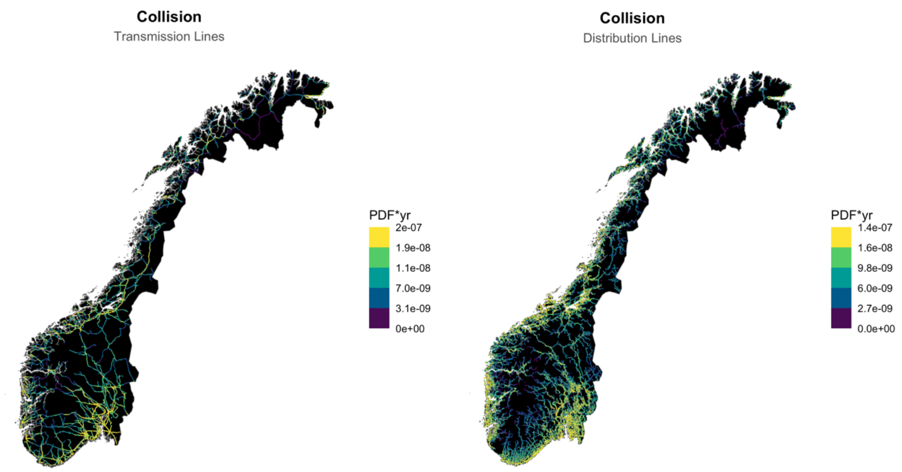

Figure S1*. PDF results for the collision impact with transmission (left) and distribution lines (right) in Norway.*

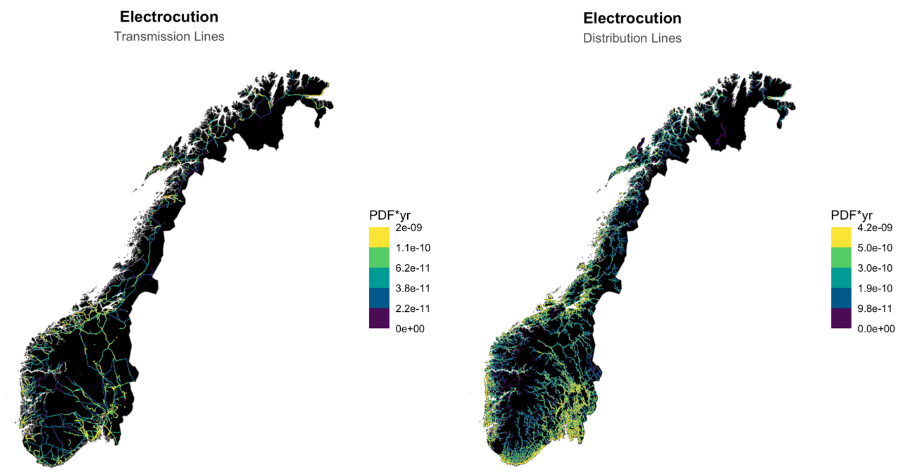

Figure S2. *PDF results for the electrocution impact with transmission (left) and distribution lines (right) in Norway.*

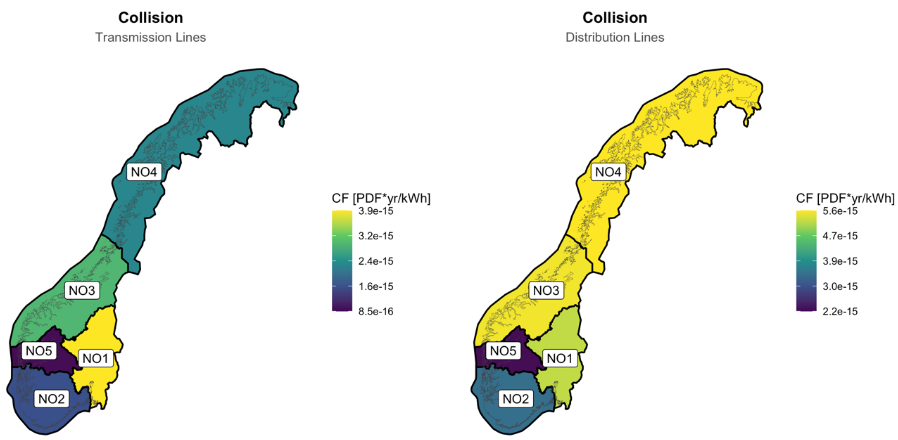

Figure S3. *Characterization factors quantifying the impacts of electricity production and consumption on bird richness in PDF*yr/kWh due to collision with transmission (left) and distribution lines (right).*

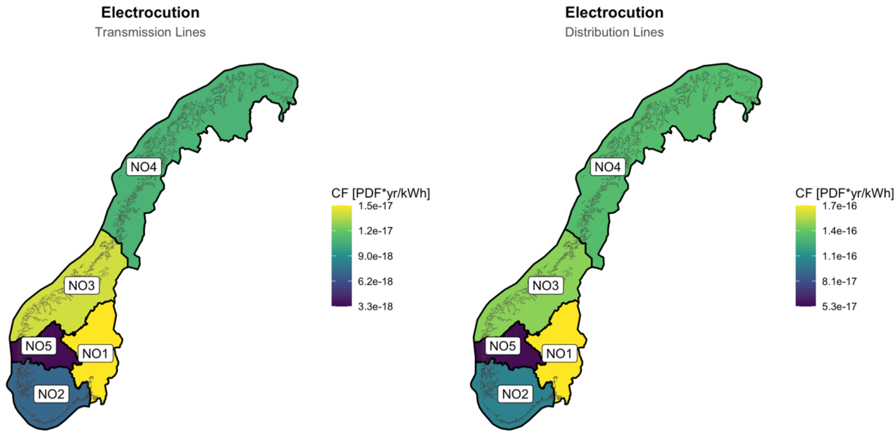

Figure S4. *Characterization factors quantifying the impacts of electricity production and consumption on bird richness in PDF*yr/kWh due to electrocution by transmission (left) and distribution lines (right).*

Sensitivity analysis

We ran sensitivity analyses for three factors: collision risk probability, wingspan, and pylon use behavior. For the collision risk probability and the wingspan, we generated 100 random values while data range and distribution within each bird group k were taken into account. For the pylon use behavior, we calculated a random range based on the given beta distribution to compute the mean value of the pylon use per bird group k. We then executed the collision and electrocution models iteratively, running them 100 times for each factor to observe the variations in the PDFs.

Boxplots were created to present the overall PDF values associated with the factor collision risk probability (collision impact) and the factors of pylon use behavior and wingspan variabilities (electrocution impact). The PDF values were generated separately for each power line type, i.e., distribution or transmission lines (S5-S6). Violin plots were conducted to illustrate how the PDF values vary within the bird species groups for each factor and per power line type (S7-9).

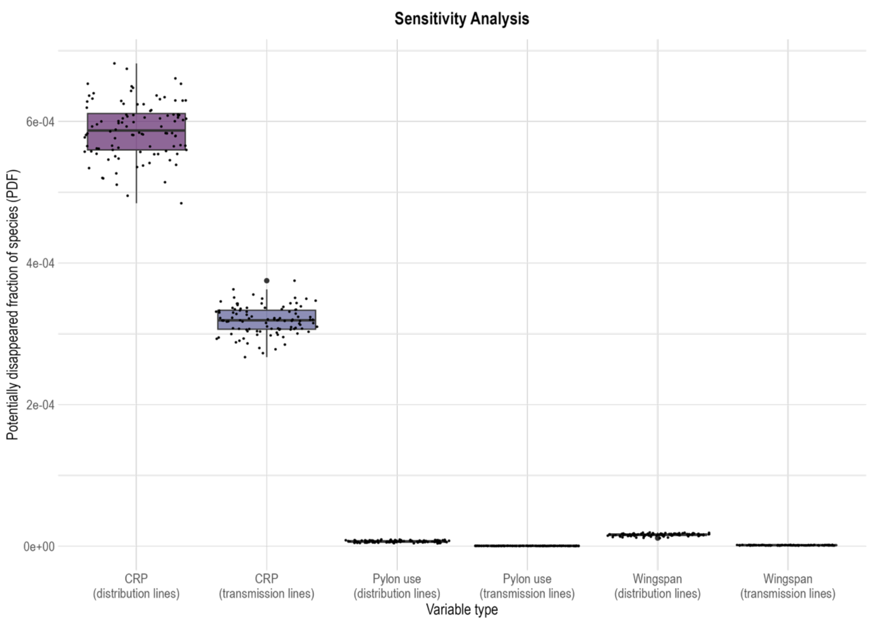

Figure S5. *Sensitivity analysis showing variation in PDF values per power line type for the collision risk probability (CRP) for the collision impact, and pylon use behavior, and wingspan factors for the electrocution impact.*

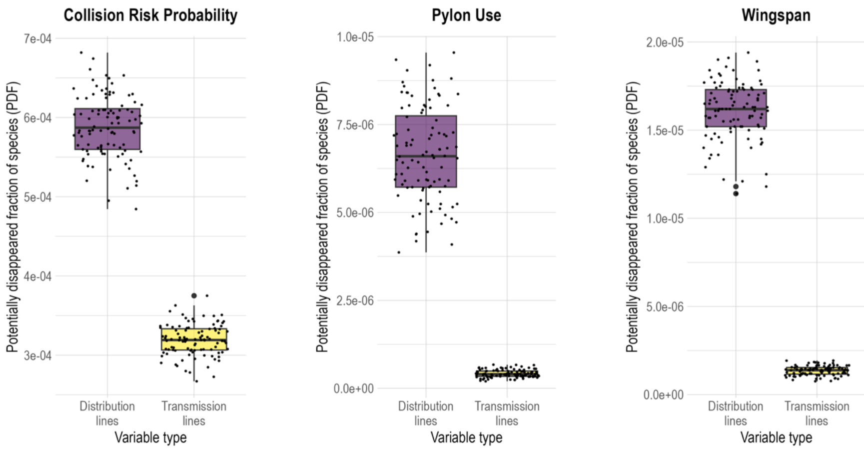

Figure S6. *Sensitivity analysis showing variation in PDF values per factor: collision risk probability for the collision impact, and pylon use, and wingspan for the electrocution impact. The colors represent the power line type: distribution (purple) and transmission lines (yellow).*

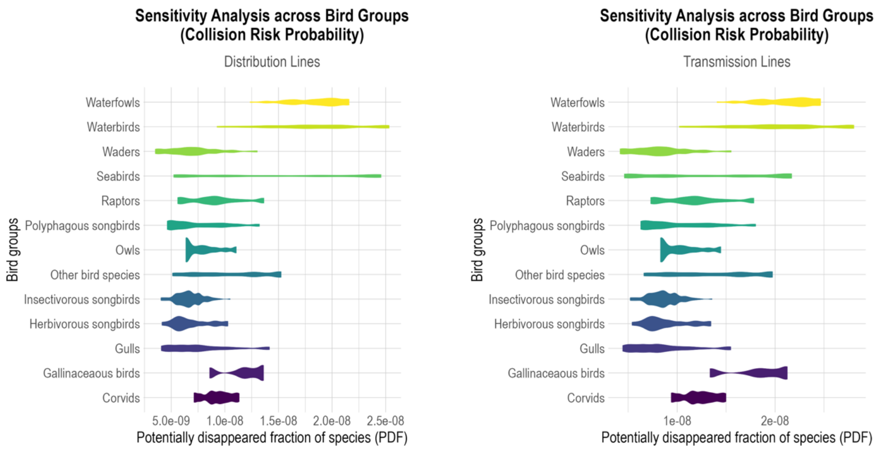

Figure S7. *Sensitivity analysis across bird groups showing variation in PDF values of the collision impact per bird group for the collision risk probability for distribution lines (left) and transmission lines (right).*

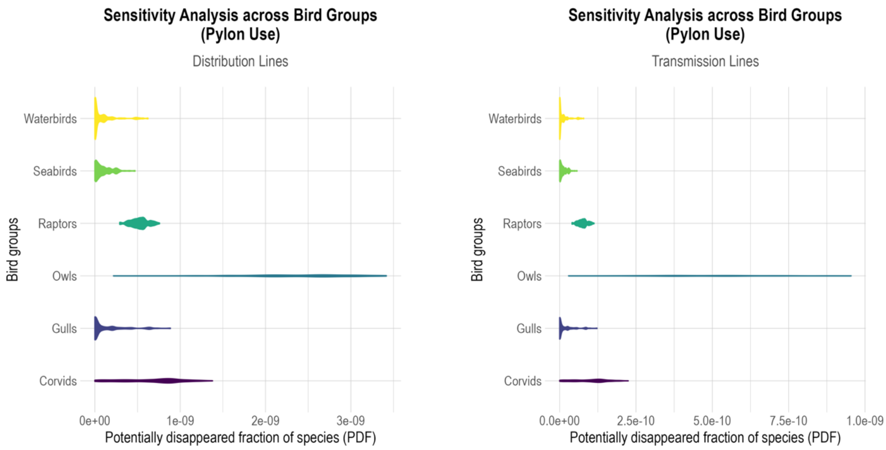

Figure S8. *Sensitivity analysis across bird groups showing variation in PDF values of the electrocution impact per bird group for the pylon use behavior for distribution lines (left) and transmission lines (right).*

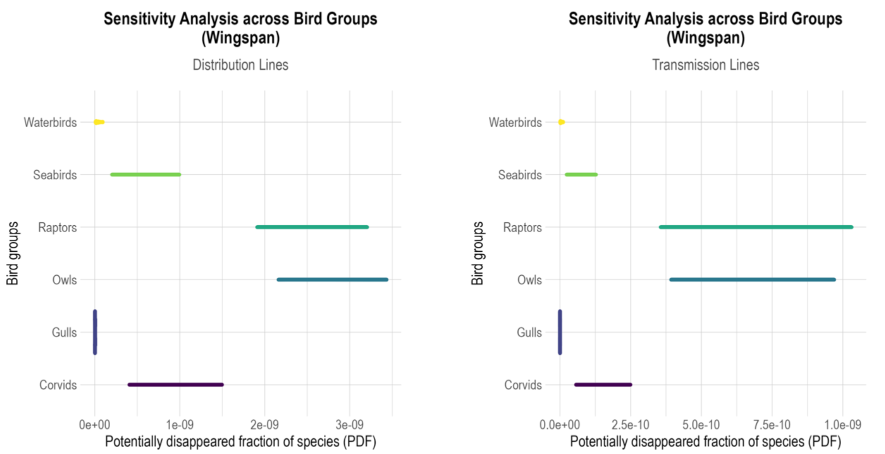

Figure S9. *Sensitivity analysis across bird groups showing variation in PDF values of the electrocution impact per bird group for the wingspan for distribution lines (left) and transmission lines (right).*

SUPPORTING INFORMATION FOR CHAPTER 3

Biodiversity on the Line: Life Cycle Impact Assessment of Power Lines on Species Richness.

This paper is awaiting publication and is not included in NTNU Open

SUPPORTING INFORMATION FOR CHAPTER 5

Biodiversity Impacts of Norway's Renewable Electricity Grid.

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