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Biodiversity impacts of Norway's renewable electricity grid

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ABSTRACT

Norway aims to transform into a low-emission nation by 2050. However, the energy transition comes with challenges, as expanding renewable energy infrastructure requires significant land areas, which raises concerns about associated environmental impacts, particularly on species richness. The first system-wide life cycle assessment (LCA) approach that integrates multiple biodiversity models is presented, evaluating the current effects of renewable energy production and transmission in Norway. The impacts of Norwegian hydropower and onshore wind power plants are quantified, which contribute 98% of Norway's electricity generation. Additionally, the effects of power lines are included to assess the spatial origins of the biodiversity impacts derived from both energy production and transmission relative to where electricity was transmitted to and consumed in Norway. The analyses show that hydropower exerts the most substantial impact on species richness and that the electric grid affects mostly mammal richness due to habitat conversion and fragmentation. As energy production primarily originates in western-central and northern Norway, regions with low electricity generation, such as south-east Norway, import a substantial share of the biodiversity impacts for their energy consumption. However, integrating an international dimension is crucial, as multiple European countries exchange energy with Norway, and thus also contribute to the pressure on local species richness. The results present the current operational impacts on biodiversity caused by Norway's electricity system. Since Norway intends to increase its renewable energy production capacity in the coming decades, this approach can serve as an instrument for developing scenarios to assess the future construction of hydropower, onshore wind power, and power lines. It can help shape Norway's energy future, ensuring a holistic approach that integrates impacts on species diversity and promotes an environmentally friendly energy transition. While focused on Norway, the methodology is adaptable to other regions if the required data is available.

1. Introduction

To address climate change, a transition towards renewable energy sources is key (Clarke et al., 2022). Norway has established ambitious goals to cut greenhouse gas emissions by 50% compared to the 1990 level by 2030 and by 90% by 2050 (KMD, 2021). A necessary strategy in reaching these objectives involves promoting electrification, particularly within key sectors, such as the petroleum and transportation sectors (KMD, 2021; NOU, 2023:3, 2023; NVE, 2023c). This rise in electrification will, however, increase electricity demand. The Norwegian Water Resources and Energy Directorate (NVE) foresees a 40% increase in energy consumption in Norway from the present to 2040 (NVE, 2023c).

In Norway, electricity accounted for a substantial 42% of the total energy consumption in 2022 (NVE, 2023f). Norwegian electricity production relies mostly on renewable energy. Hydropower and wind power constitute 98% of the nation's electricity production in 2022 (88% and 10%, respectively) (SSB, 2023b). Although prioritising electricity efficiency and electrification are crucial in the energy transition, additional electricity production is essential to ensure the country's energy security (NOU, 2023:3, 2023; NVE, 2023c).

While Norway strives to fulfil its commitments to the Paris Agreement and the European Union to reduce its emissions (KMD, 2021; OED, 2021), the country is also committed to protecting its biodiversity by conserving ecosystems and species and preserving Norwegian nature for future generations (KMD, 2015). Given that habitat change (i.e., loss, degradation, or fragmentation) poses the greatest threat to Norwegian species (Artsdatabanken, 2021), one of the national biodiversity goals in

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Norway was to decrease the rate of natural habitat loss by 2020 (KMD, 2015). However, upcoming construction projects in Norway, including plans for energy production infrastructure, can potentially diminish forest areas, natural open vegetation, and peatlands (Simensen et al., 2023). The construction of hydropower plants can lead to the loss of terrestrial habitats due to land inundation, alter freshwater habitats through fragmentation and changes in water flow, and impact water quality (Geist, 2021; Gracey and Verones, 2016). Habitat loss, barrier effects, and the risk of collision are known impacts of wind farms on wildlife (Laranjeiro et al., 2018; Rydell et al., 2012). An integral component of energy production is the electric grid, which transmits the generated electricity to consumers. However, power lines exert pressure on biodiversity, too, contributing to the conversion and fragmentation of natural habitats and posing risks of collision and electrocution for birds (Bernardino et al., 2018; Biasotto and Kindel, 2018; Richardson et al., 2017).

It is vital to gain a deeper understanding of the current magnitude and distribution of the impacts of electricity production and transmission on Norwegian ecosystems. Therefore, we need a holistic approach to identify where mitigation measures should be enforced and where future construction plans potentially impact biodiversity. This is particularly important because strategic planning serves as a crucial mitigation measure to reduce the magnitude of the effects on local biodiversity from hydropower (Zarfl et al., 2019), wind power (Bulling and Köppel, 2016; Rydell et al., 2012), and power lines (Bernardino et al., 2018; D'Amico et al., 2018).

Numerous studies have explored the ecological impacts of renewables in Norway (Forseth et al., 2014; Haraldstad et al., 2021; Kjærstad et al., 2018; May et al., 2013; May et al., 2011). However, these studies focused on different impacts and used diverse methodologies that hinder comparability.

Life cycle assessment (LCA) is an approach that allows the assessment of multiple impacts from various emissions and resource uses in different impact categories (e.g., climate change, land use, and resource depletion). Since LCAs are able to assess these impacts simultaneously, comparisons between technologies and across impact categories, as well as identifications of trade-offs, are possible (Hellweg et al., 2023). It is, therefore, a suitable tool to identify the trade-offs between promoting renewable electricity production and conserving biodiversity. An LCA consists of four phases, namely goal and scope (what is the comparative system and functional unit), life cycle inventory collection (which resources are used and which emissions are generated), life cycle impact assessment (LCIA) (how do these inventory parameters translate to environmental impacts in different categories) and interpretation (Hellweg et al., 2023). Many LCIA models that are relevant for biodiversity impacts are spatially explicit and thus account for regional impacts rather than using site-generic models (Hellweg et al., 2023). For instance, Dorber et al. (2020a) highlighted how important site selection is to reduce future global biodiversity impacts of hydropower reservoirs.

There are a number of LCIA models available that were explicitly applied to Norway due to the comparatively good data availability. These include impacts of hydropower (Dorber et al., 2019), onshore wind power (May et al., 2021), and power lines (Gilad et al., 2024a,b). These models focused only on singular technologies and specific impact pathways. Furthermore, a new global LCIA model for impacts from water consumption (Pierrat et al., 2023) has not yet been applied to renewable energy production.

In this study, we adopt these existing impact models within the LCIA framework to conduct the first system-wide quantification of biodiversity impacts associated with the current operation of Norway's electricity system. This assessment establishes a baseline for future assessment scenarios for expanding electricity generation in Norway. We used and adapted existing Norwegian models and incorporated an additional global model to quantify the overall biodiversity impact of habitat loss by land inundation or supplementary infrastructure and water consumption due to hydropower plants; barrier, collision, disturbance, and habitat loss caused by wind power plants; and the effects of collision, electrocution, as well as habitat conversion and fragmentation from power lines. Our methodology uses the spatial unit of the Norwegian pricing areas, demarcated into five regions, highlighting the spatial variation in electricity production and consumption across these regions. The pricing areas allow us to illustrate where the impacts associated with generating and transmitting electricity originated from and identify where this electricity is ultimately consumed.

2. Material and methods

2.1. Impact quantification

We used nine existing LCIA models to evaluate the main impacts of energy production and transmission on biodiversity in Norway (see Table 1). All the models use the relative impact metric of the potentially disappeared fraction of species (PDF), a recommended metric within the LCIA framework (Verones et al., 2017; Woods et al., 2018). The generated values represent a potential reduction in species richness due to certain stressors rather than providing precise estimations of the number of individual species that will be lost. The LCIA models we incorporated employ three adapted versions of species accumulation curves to calculate the PDFs: the species-area relationship (SAR), the species-habitat relationship (SHR), and the species-discharge relationship (SDR).

The core idea behind a SAR is that an area can support a certain number of species. A reduction in the area size leads to a decrease in the number of species. SAR models are commonly used for assessing land use impacts on terrestrial biodiversity (Chaudhary et al., 2015; Dorber et al., 2020b).

The SHR model builds upon the SAR approach by incorporating the so-called equivalent connected area. Here, rather than addressing only the changes in habitat size, the model considers the dispersal probability of species and the number, spatial configuration, and size of habitat patches. Hence, SHR models quantify the impacts of habitat conversion and also account for fragmentation effects (Kuipers et al., 2021a, 2021b; Scherer et al., 2023).

Both SAR and SHR models use a constant value (z) to denote the relationship's slope. We assigned the z values suggested by Storch et al. (2012) for birds and mammals in Eurasia (0.21 and 0.26, respectively).

Finally, SDR models are based on the positive correlation between freshwater species richness and the mean annual discharge (Xenopoulos and Lodge, 2006). Therefore, biodiversity loss can be derived from

Table 1
Existing LCIA models used or adapted to assess the impact pathways of renewable energy production and transmission on biodiversity. The mammals only include non-flying mammals.

Technology	Impact	Species groups	Species relationship	References
Hydropower	Habitat loss	Birds, terrestrial mammals	SAR	cf. May et al. (2021)
	Water consumption	Fish	SDR	Pierrat et al. (2023)
Wind power	Barrier	Birds	SAR	May et al. (2021)
	Collision Disturbance			May et al. (2020a)
	Habitat loss	Birds, terrestrial mammals		
Power lines	Collision Electrocution	Birds	SAR	Gilad et al. (2024b)
	Habitat conversion and fragmentation	Birds, terrestrial mammals	SHR	Gilad et al. (2024a)

yearly alterations in river discharge. The SDR model is used in LCIA for quantifying the impacts of water consumption on aquatic biodiversity.

2.1.1. Species occurrences

Species richness for terrestrial species was derived from species distribution maps developed by May et al. (2021) for birds and by Gilad et al. (2024a) for mammals. These maps represent relative habitat suitability estimates and provide a likelihood of species presence across Norway. They are well-suited for assessing the impacts of energy infrastructure because they capture spatial variability on a pixel level. The bird and mammal species were aggregated into subgroups based on ecological taxonomy and functionality: 13 bird subgroups and four mammal subgroups (Gilad et al., 2024a; May et al., 2021).

Pierrat et al. (2023) used range maps of riverine fish to assess the impact of water consumption on fish species richness. After excluding the introduced species from the riverine fish dataset, we used the dataset of Pierrat et al. (2023) to extract the number of native species in Norway and each catchment to account for the regional species loss.

2.1.2. Hydropower

We quantified two impact pathways of hydropower on biodiversity: terrestrial habitat loss and water consumption. The impact of habitat loss from hydropower plants was quantified based on the extent of area lost due to land inundation (HINU) and associated infrastructure (HINF). Global LCIA models are available for quantifying terrestrial biodiversity impacts of land inundation (Dorber et al., 2020b) and land use (Scherer et al., 2023). However, these models rely on ecoregions as the spatial unit for assessing species richness. While suitable for a global perspective, ecoregions are not detailed enough for Norway. Therefore, instead of applying these models, we adopted an approach that allows impact quantification at a pixel level. We computed impacts at the pixel level because we derived the number of species per pixel from the species distribution maps (1 km^2).

Dorber et al. (2018) assessed inundated areas by Norwegian reservoirs, using remotely sensed data to quantify the expansion of the water surface following dam constructions. Their study analysed Norwegian hydropower reservoirs, encompassing 808 km^2 inundated areas.

To quantify the impact of habitat loss resulting from reservoir creation, we assessed the reduction in the original habitat ($A_{org} = 1\ km^2 =$ one pixel) by the inundated area within pixel *i* ($A_{i,inundated}$). The calculation of the inundated areas was determined per reservoir (n = 90) by assessing the coverage of the area that became inundated within the pixel cell *i* based on data from Dorber et al. (2018).

We then calculated the number of species belonging to group *k* per pixel *i*. However, the species distribution maps for birds and mammals were based on species occurrence data collected between 2010 and 2019. They may not accurately reflect the number of species in the area before the inundation. Moreover, these maps rely on environmental predictors, including a land cover map from the year 2018 (C. Jackson, personal communication, Dec 8, 2023). The land cover map classified reservoirs as lakes, including areas that are now inundated. Assigning the number of species within the pixels of the inundated areas could result in inaccuracies in species presence probabilities, particularly for terrestrial species drawn to water sources, i.e., forage in aquatic ecosystems. For example, the species distribution map of the Osprey (*Pandion haliaetus*) identified waterbodies as areas with a high likelihood of species presence.

Consequently, considering inundated areas as non-waterbodies may lead to overestimating species presence, depending on species-specific traits. To tackle this issue, we introduced a species water index. For each species, we computed the mean of three foraging behaviour elements: 1) the proportion of fish in the species' diet, 2) the percentage of foraging activity underwater, and 3) the percentage of foraging activity on water surfaces. The foraging data were obtained from the EltonTraits dataset (Wilman et al., 2014). We derived a mean value for each species, subtracted it from one, and used this result as a weighting factor to highlight which species are attracted to water bodies. Subsequently, we adjusted each species distribution map by multiplying it with its corresponding weighting factor. This adjustment reflects the estimated presence of each species in the area before inundation occurred.

Next, we established a 1 km buffer (*d*) around each inundated area (i.e., the current reservoir area). We calculated the mean number of species of group *k* within the pixels ($S_{d,k}$). We assumed that the area surrounding the reservoir represented the potential presence of species before the inundation. The overall number of species was determined by summing the number of species of group k across Norway ($\sum S_{i,k}$) (Eq. (1)).

$$PDF(HINU)_{i,k} = \frac{S_{d,k} \bullet \left(1 - \left(\frac{A_{org} - A_{i,inundated}}{A_{org}}\right)^{z}\right)}{\sum S_{i,k}} \tag{1}$$

We quantified impacts for each species group *k* per pixel *i*. We then aggregated the pixels surrounding each reservoir, deriving an impact per reservoir and assigning hydropower plants (n = 724) to each reservoir. The impact caused by that reservoir was then distributed proportionally among the connected hydropower plants, considering their respective shares of electricity production. If connected to a reservoir, one hydropower plant can be partly responsible for the impacts of several reservoirs. For instance, if a hydropower plant contributed 70% of the electricity generated by all power plants connected to a reservoir, it was assigned 70% of the reservoir's impact.

Area losses associated with supplementary infrastructure were retrieved for both small-scale (generating less than 10 megawatts [MW]; n = 59) hydropower plants (Hedger et al., submitted) and large-scale (generating more than 10 MW; n = 33) hydropower plants (Kenawi et al., 2023). These estimates represent areal losses from required infrastructure related to hydropower, such as clearance areas, dams, and roads. We used a logspline density estimation to assess a probability density function describing the distribution of the gathered data set (see the sensitivity analysis in Supporting Information 2). This distribution was used to infer habitat loss caused by infrastructure across Norwegian hydropower plants not included in the data from Hedger et al., submitted and Kenawi et al. (2023) (n = 1675). The area lost (a_{EP}) for each power plant was then calculated based on its MW capacity (EP_{hp}). As the exact spatial location of the areal loss of each power plant is unknown (e.g., access roads), we allocated the impact across the nine cells surrounding the power plant. The impacts were estimated using the area lost per hydropower plant (hp) in each pixel cell *i*, adapted from the equation of May et al. (2021), who assessed the direct and indirect area losses of wind power plants (Eq. (2)):

$$PDF(HINF)_{k,hp} = \frac{S_{i,k} \bullet \left(1 - \left(\frac{A_{org,i} - a_{EP} EP_{hp}}{A_{org,i}}\right)^{z}\right)}{\sum S_{i,k}} \tag{2}$$

We derived the net water consumption (in m^3) caused by the reservoir creation from Dorber et al. (2019) and average regional characterisation factors describing the PDF * year (yr)/m^3 water consumption from Pierrat et al. (2023). As the impacts were originally calculated per catchment, we standardised them across Norway for comparability: we multiplied the impacts by the respective sum of fish species in each catchment. Subsequently, we divided the results by the sum of fish species found throughout all catchments in Norway. Similarly to habitat loss, we aggregated the water consumption impact per reservoir and allocated it to hydropower plants (n = 676) based on their electricity production shares.

In total, there are 1781 hydropower plants in Norway (NVE, 2023h). Among these, the three impact pathways cover 724, 1,767, and 676 hydropower plants (habitat loss due to land inundation, habitat loss due to infrastructure, and water consumption, respectively). Notably, these power plants contributed at least three-quarters of the annual average Norwegian electricity produced by hydropower between 1990 and 2020 (NVE, 2023b). Hydropower plants and reservoir data were downloaded from NVE (NVE, 2023d).

2.1.3. Wind power

May et al. (2020a, 2021) quantified the impact pathways of barrier effects, collision, disturbance, and habitat loss on bird diversity. While the impacts of the first three impact pathways relate specifically to bird species (i.e., migration distances, collision rates, or flight initiation distances, respectively), the habitat loss impact was based solely on area requirements. Therefore, we added the habitat loss impact on mammal richness based on the methodology described by May et al. (2021). The impacts were calculated for each subgroup separately. Impacts were calculated per turbine and then aggregated per power plant. We assessed the four impacts for all operating wind power plants (n = 63) in 2022 (NVE, 2023a). Wind turbine data and corresponding rotor sizes were downloaded from NVE (NVE, 2023d). Unknown rotor sizes were estimated using linear regression ($r^2 = 0.94$). Note that in the original NVE database, there are 65 wind farms. However, Raggovida and Raggovida 2 and Raudfjell and Kvitfjell were merged manually for subsequently matching both the rotor and spatial geodata datasets.

2.1.4. Power lines

Gilad et al. (2024a,b) estimated the impacts of collision, electrocution, and habitat conversion and fragmentation caused by power lines. The characterisation factors (PDF * yr/kWh) quantified the biodiversity impacts of power lines and their associated pylons, classified as transmission (equal to or exceeding >60 kV) and distribution lines (below 60 kV) by the voltage of each power line section. While collision, habitat conversion and fragmentation quantify the impacts of transmission and distribution lines, electrocution only applies to distribution lines.

In addition, the impact pathways for collision and electrocution are only relevant for bird species, while habitat conversion and fragmentation impacts were assessed for birds and mammals. Although LCIA impacts are commonly assessed at the ecoregion level (Pierrat et al., 2023; Scherer et al., 2023; Verones et al., 2017, 2022), the approaches of Gilad et al. (2024a,b) focused on a landscape region level due to their larger spatial detail. There are 45 Norwegian landscape regions distinguished by landforms, geological composition, water and waterways, vegetation, agriculture, and urban areas (Puschmann, 2005). Power lines and pylon data were obtained from NVE (NVE, 2023d).

While most of the Norwegian electricity transmission originates from renewable sources, electricity is also imported into Norway from neighbouring countries. Notably, imported electricity is not necessarily from renewables.

2.2. Impact allocation to pricing areas

We selected the Norwegian pricing areas as the spatial aggregation unit to quantify the biodiversity impacts of electricity production, consumption, and transmission. Norway is divided into five electricity pricing areas: Eastern Norway (NO1), Southern Norway (NO2), Central Norway (NO3), Northern Norway (NO4), and Western Norway (NO5) (see Fig. 5). These regions play a crucial role due to spatial variations in electricity production and consumption. For example, NO1 has a high electricity consumption but contributes minimally to Norwegian energy production. NO4, on the other hand, produces a significant amount of energy but has lower electricity consumption. The Norwegian electric grid cannot freely transmit electricity across all pricing areas. Therefore, electricity must flow from one pricing area to another (Statnett, 2022a). The pricing areas can illustrate the spatial dynamics involved in electricity production within a specific pricing area, its transmission across different areas, and its consumption in other regions. While impacts may occur in a certain area, the electricity demand might originate elsewhere in Norway.

2.2.1. Characterisaction factors at pricing areas level

We assigned each power plant (i.e., hydropower or wind power plant) and its calculated impacts spatially to the pricing area where they are located. For the transmission and distribution lines (power line type pl), where impact pathways (X) were calculated per landscape region, we allocated the impacts of each species subgroup to the pricing areas (PA) based on the proportion of the area (A) of landscape region *j* within each pricing area (Eq. (3)).

$$PDF(X)_{k,PA,pl} = \sum_j PDF(X)_{k,j,pl} \bullet \frac{A_{j,PA}}{A_{PA}} \tag{3}$$

To aggregate the subgroups to the taxon level, we calculated the mean of all the species groups per impact pathway (i.e., habitat loss and collision) and technology (i.e., wind power or hydropower). Fish species were assessed as a single taxon, eliminating the need for aggregation.

The final characterisation factors for each impact pathway X and taxon *t* were computed by aggregating impacts across pricing areas and dividing the PDF * yr by the annual energy production or consumption (E) in GWh within the regions (Eq. (4)).

$$\mathrm{CF(X)_{PA}} = \frac{\sum PDF(X)_{t,PA}}{\mathrm{E_{PA}}} \tag{4}$$

For the hydropower or wind power plants, the annual energy production of each technology was divided from the PDFs for each pricing area. Since distribution lines transmit electricity to consumers, the biodiversity impacts were divided by the annual electricity consumption data within each pricing area (ENTSO-E, 2023). As transmission lines facilitate the delivery of electricity demand and transmission across pricing areas, we calculated the sum of electricity locally consumed in each pricing area and the exported electricity (ENTSO-E, 2023). The PDFs of the transmission lines were then divided by this combined sum per pricing area.

Sensitivity analyses were conducted for each impact pathway and technology (see Supporting Information 2, Figs. S3–4).

2.2.2. Electricity network analysis

We analysed the electricity network based on hourly electricity production and consumption data in MW for 2022 for each Norwegian pricing area (ENTSO-E, 2023). The dataset also encompasses cross-border flow data, illustrating the energy flow between Norwegian pricing areas and its exports to and imports from Europe at hourly resolution. The analysis aimed to calculate the share of the electricity flows between the pricing areas. We analysed the pricing areas by their corresponding electricity production and consumption data in a matrix.

Power producers initially sell electricity within their respective pricing areas. In case of a surplus or deficit, electricity is transferred to or from the other pricing areas (Statnett, 2021). Therefore, we subtracted the electricity consumption from the production in each pricing area to determine the locally consumed electricity.

An operational grid system must ensure a continuous balance between electricity production, consumption, export, and import (NVE, 2022). So, any electricity produced in a specific pricing area exceeded local consumption was classified as surplus electricity. Given Norway's positive energy balance, the country can independently satisfy its own electricity needs (NVE, 2022). Therefore, we assumed that surplus electricity was redirected to a Norwegian region in need when electricity was generated in a certain pricing area but not consumed locally. If surplus electricity production exceeded the demands of Norwegian pricing areas, we classified it as exports to connected pricing areas in Europe (i.e., Finland, Sweden, Denmark, Great Britain, the Netherlands, and Germany).

To calculate the portion of electricity produced in pricing area *b* but consumed in pricing area *a*, we used the following equation (Eq. (5)):

$$E_{a,b,production} = \frac{E_{PAa,demand}}{\sum E_{demand}} \bullet E_{PAb,surplus} \tag{5}$$

$E_{PAa,demand}$ represents the residual electricity demand in pricing area *a* (i.

e., domestic electricity production did not meet the demand and thus requires import from other pricing areas). This demand was then proportionally allocated to the other Norwegian regions and Europe (abroad) by dividing it by the sum of the residual electricity demand across all pricing areas, including the European countries. This calculation provided the proportionate share of the electricity demand for pricing area a. The share was multiplied by the remaining surplus electricity ($E_{PAb,surplus}$) produced in pricing area b (i.e., electricity produced in pricing area b and not consumed locally).

Similarly, to compute the share of electricity transmitted through pricing area b but consumed in pricing area a, we followed equation (Eq. (6)):

$$E_{a,b,transmission} = \frac{E_{PAa,demand}}{\sum E_{demand}} \bullet E_{PAb,transmitted} \tag{6}$$

Here, the proportionate share of electricity needed in pricing area a was multiplied by the amount of electricity transmitted but not locally consumed in pricing area b ($E_{PAb,transmitted}$). We normalised $E_{a,b,transmission}$ by the total electricity transmitted within pricing area a. This was the share of electricity transmitted from pricing area b to meet the demand in pricing area a.

We aggregated the hourly data to annual data to calculate the proportionate shares of electricity production and transmission for each pricing area in 2022, encompassing all regions and accounting for imports and exports from European countries. See Supporting Information 2 (Table S1 and Figs. S1–2) for an example.

Finally, we aggregated the overall impact for each pricing area, incorporating all the impacts pathways of energy production and transmission. The total impact of pricing area b was divided by the proportional shares of pricing area a with respect to the electricity produced ($E_{a,b,production}$) in or transmitted ($E_{a,b,transmission}$) from pricing area b. This represented the impact originating in pricing area b but transmitted to and consumed in pricing area a. We computed these shares across all pricing areas, assessing the proportion of biodiversity impacts transmitted to and consumed by the other pricing areas.

All the data analysis was conducted with R version 4.3.1 (R Core Team, 2023) in RStudio version 2023.06.0 + 421. Codes are available in the repository provided in Supporting Information 2.

3. Results

3.1. The impacts of renewable energy on biodiversity

Among the various impact pathways, habitat change – characterized by habitat loss, conversion, or fragmentation – emerged as the primary contributor to affecting terrestrial biodiversity in Norway. A high share of the habitat loss impact originated from power lines (7.11×10^{-4} PDF * yr), followed by hydropower (6.15×10^{-4} PDF * yr) and wind power (2.8×10^{-5} PDF * yr). Additionally, water consumption associated with hydropower reservoirs significantly affected freshwater fish (5.1×10^{-4} PDF). Collisions with power lines or wind turbines had more pronounced impacts on birds (1.48×10^{-4} and 2.14×10^{-6} PDF * yr, respectively) than barrier effects (3.64×10^{-6} PDF * yr) and electrocution (4.2×10^{-6} PDF * yr) impacts. Mammal diversity was the most affected, followed by birds and freshwater fish (see Fig. 1 and Tables S1–S5 in Supporting Information 1).

3.2. Impacts in the pricing areas

Hydropower substantially impacts species richness (see Figs. 2 and 5a and Table S6 in Supporting Information 1), especially in NO3 and NO5. In NO3, the impacts of wind farms on biodiversity were most pronounced, primarily attributed to habitat loss and disturbance (see Fig. 2).

The biodiversity impact of electricity transmission was highest in NO1, where both distribution and transmission lines greatly affected species richness (see Figs. 3 and 5a and Table S6 in Supporting Information 1). Moreover, distribution lines demonstrated a substantial biodiversity impact in NO5, while NO4 exhibited the least effect of electricity transmission on species richness across all five regions. Notably, habitat conversion and fragmentation emerged as the dominant impact pathway, affecting bird and mammal diversity. The collision impact posed a higher risk for birds than electrocution, particularly in NO1 and NO5 (see Fig. 3).

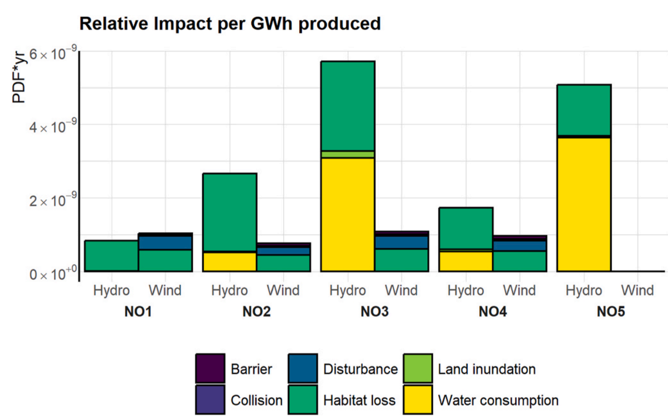

Fig. 2. The relative biodiversity impact (i.e., the potentially disappeared fraction of species; PDF * yr) per GWh produced caused by each specific impact pathway and shown across the Norwegian pricing areas and main technologies, i.e., wind power and hydropower.

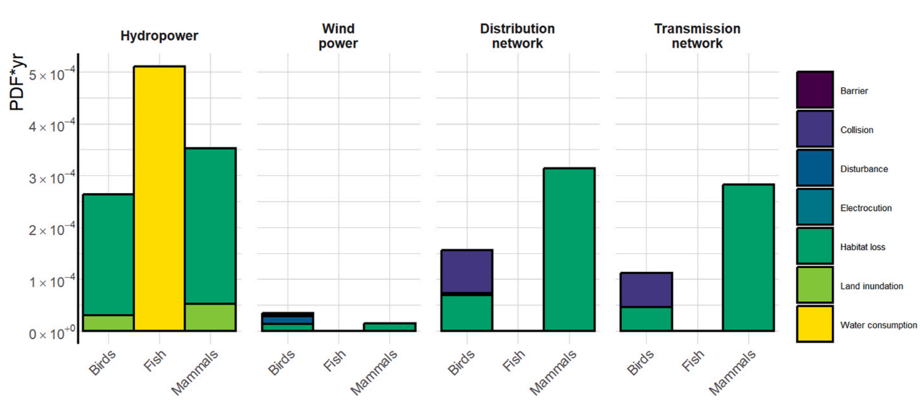

Fig. 1. The biodiversity impact pathways (hydropower, wind power, and power lines – distribution and transmission lines) and their effect per species taxon (birds, fish, and mammals) in PDF (i.e., potentially disappeared fraction of species * yr) units.

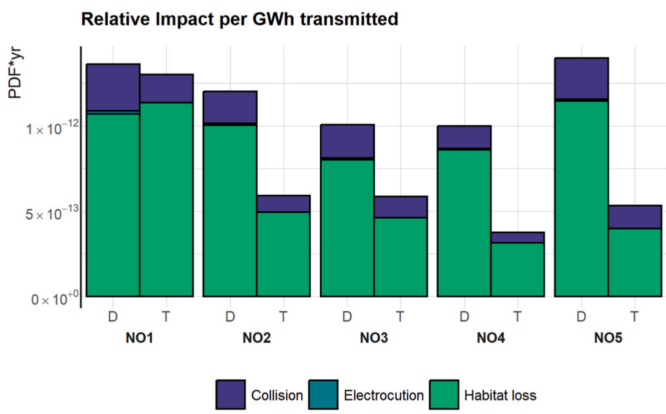

Fig. 3. The relative biodiversity impact (potentially disappeared fraction of species; PDF * yr) per GWh transmitted caused by each specific impact pathway and shown across the Norwegian pricing areas and distribution (D) as well as transmission (T) network.

3.3. Contribution of biodiversity impacts across pricing areas

Overall, each pricing area is the primary source of electricity production and transmission for its own area. Pricing areas NO2 and NO3 are the top electricity producers (see Fig. 4a), while NO1 and NO2 transmit the most electricity (see Fig. 4b). NO1 heavily relies on other pricing areas, especially NO2, NO4, and NO5, to meet its electricity demands. Despite being a significant electricity producer, NO2 still requires electricity from NO4, NO5, and NO3. NO4 is the only region not requiring electricity from other pricing areas.

This trend mirrors electricity transmission, where all pricing areas transmit electricity to NO1. Electricity is also transmitted to NO2 and NO3 from all the pricing areas. Conversely, NO4 does not rely on electricity transmission from other regions.

European countries contribute to Norway's electricity supply and export dynamics by producing and transmitting electricity into Norway, prominently to NO1. However, our focus is directed solely towards electricity export, as it represents the impacts on species richness in Norway. European countries also consume electricity generated in Norway, particularly electricity that originated from NO5, NO2, and NO3. The primary channels for electricity transmission to Europe are NO2 and NO5, but electricity to Europe traverses from the rest of the pricing areas (Tables S7–8 in Supporting Information 1).

When examining the overall biodiversity impact of electricity production and transmission across pricing areas, the primary contributor is the respective pricing area (see Fig. 5b). For example, most of the impact

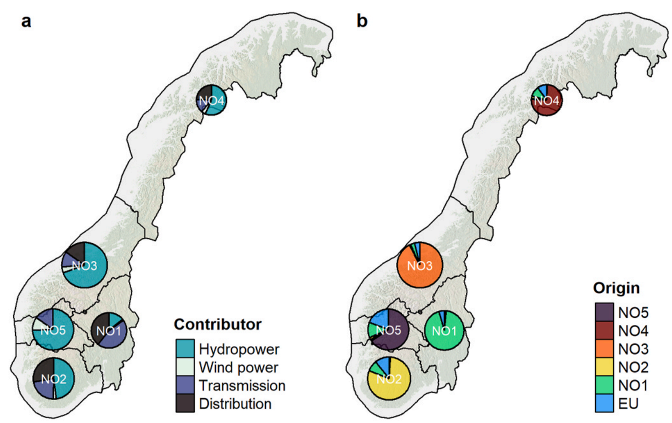

Fig. 5. a) Magnitude and distribution of the overall impact from electricity production (hydropower and wind power) and transmission (distribution and transmission lines) as attributed to the respective Norwegian pricing areas. The relative circle size corresponds to the magnitude of the overall impacts experienced within the pricing areas. For example, hydropower accounts for two-thirds of the overall impact in NO3, while over a quarter is attributed to power lines. **b)** Distribution of impact shares from electricity production and transmission within the Norwegian pricing areas, including export to Europe. For example, NO5 has the highest impact share of its pricing area, but the impact is also exported to Europe, NO1, NO2, and NO3.

of NO2 results from the electricity produced and transmitted within it. Nevertheless, among the pricing areas, NO1 and NO3 emerge as the foremost contributors to the impact on species richness. This is particularly true for NO1, where most of its impact originates within its region. However, it contributed to biodiversity impacts originating in all pricing areas. NO3 is also a large contributor to the overall biodiversity impact, with less than eight per cent of its impact induced from other regions. Approximately one-third of the biodiversity impact from NO5 was attributed to other regions, primarily Europe (18.9%) and NO1 (11.8%). European countries also contributed to some extent to the Norwegian biodiversity impact (overall, nearly 10%). Electricity produced in and transmitted from Norway reached Europe through all the pricing areas, especially from regions NO5 and NO2. In contrast, NO4 had the least impact on species richness, as it did not rely on other pricing areas (see Tables S6–7 in Supporting Information 1).

4. Discussion

In this study, we combined and adapted existing LCIA models to quantify the operational impacts of renewable electricity production

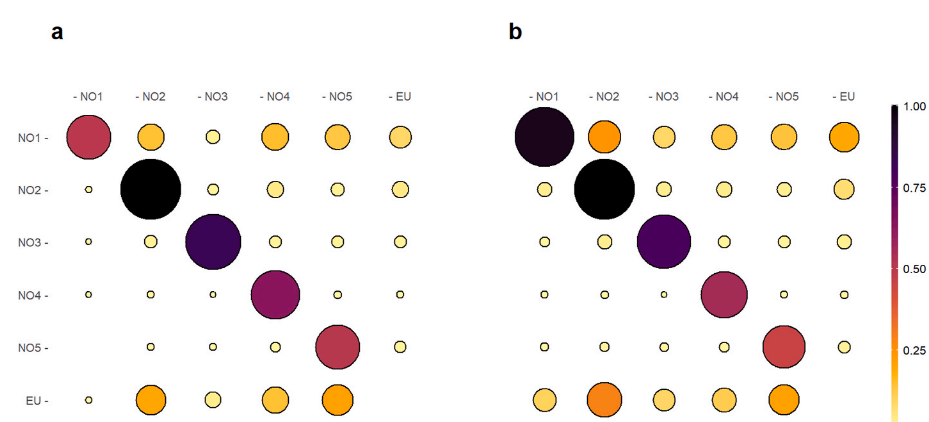

Fig. 4. a) The share of electricity production across pricing areas. **b)** The share of electricity transmission across pricing areas. The columns represent the electricity produced or transmitted within each area, while the rows indicate the pricing areas that require the electricity produced or transmitted. Darker and larger circles show a high share of electricity production or transmission between the two areas.

and transmission on biodiversity in Norway. Our assessment focused on the present effects of hydropower, wind power, transmission, and distribution lines on biodiversity across five pricing areas in Norway. By analysing the electricity network, we showed how regions distribute and import impacts originating from production sites.

Our findings show the current biodiversity impacts of renewable energy production and transmission. Hydropower contributes primarily to these impacts, affecting all three taxonomic groups. This aligns with the fact that most of Norway's electricity is derived from hydropower, supported by an extensive infrastructure comprising 1769 power plants (NVE, 2023b) and approximately 1400 reservoirs (NVE, 2023e). Most of Norway's hydropower plants were built from the 1960s to the 1980s when electricity production was more important to the country than preserving its nature (Tellefsen et al., 2020). While renewable energy resources are weather-dependent, hydropower stands out for its flexibility in balancing energy consumption and production (NOU, 2023:3, 2023; NVE, 2020, 2022). The reservoirs provide a storage capacity, enabling controlled water release to generate electricity during periods of shortage, ensuring a consistent power supply (NVE, 2022, 2023e).

Following hydropower, electricity transmission greatly impacted Norwegian biodiversity – especially the distribution grid. Normally, the width of the rights-of-way – where power lines are positioned, and vegetation is cleared – is considerably wider for transmission lines than distribution lines. However, the distribution grid covers a larger area. About 63% of the Norwegian grid operates below 60 kV (NVE, 2023d). Initially, the Norwegian grid consisted primarily of distribution lines constructed in the early 1900s to connect communities to small hydropower plants. It was not until the 1980s that the national grid was fully completed (Aas et al., 2014; NVE, 2010).

Habitat conversion and fragmentation caused the highest impact on species richness due to power lines. Since more than a third of Norway is covered by forests (37%; SSB, 2023), some forested areas were cleared to create safe corridors for power line construction, fragmenting the forest landscape. A SHR model was used to account for habitat loss and connectivity to quantify the impact of habitat conversion and fragmentation. In contrast, the habitat loss impacts of hydropower and wind power were assessed using SAR models, which only consider area loss. Since SHR models yield higher impacts in fragmented landscapes (Kuipers et al., 2021b), it may explain why the habitat conversion and fragmentation characterisation factors are relatively high.

The smaller impact associated with wind power can be explained by the lower number of onshore wind farms compared to hydropower plants, with wind power contributing only 10% to the country's electricity production in 2022 (SSB, 2023b).

Our study successfully combined the currently existing biodiversity LCIA models but still has its limitations. The included biodiversity LCIA models are limited in taxon group coverage and impact pathways, which may lead to an underestimation of the total impact. The impacts of hydropower plants, for example, are restricted to water consumption and habitat loss from infrastructure construction and land inundation. Further, water consumption impacts are restricted to the fish taxon due to data availability for the SDR. Hence, impacts on aquatic plants and macro-invertebrates could not be covered in this study.

Yet other impact pathways remained unassessed, such as changes in the natural water flow beyond the flow magnitude, river fragmentation, water temperature changes, and sediment trapping (Gracey and Verones, 2016). While the coverage of impact pathways for wind power and power lines is relatively comprehensive, the available models only account for birds and non-flying mammals. Nevertheless, bats can collide with wind turbines (Gaultier et al., 2020; Thaxter et al., 2017) and be electrocuted by power lines (Tella et al., 2020). Due to low data availability, these models could, however, so far not include bats.

Additionally, our assessment of habitat loss due to inundation focuses solely on birds and mammals, while Dorber et al. (2020b) showed that global land inundation impacts also affect reptiles and amphibians. Similarly, the habitat loss impact of wind power and power lines was modelled only on birds and mammals. We did not cover taxon groups like vascular plants, macro-invertebrates, reptiles, and amphibians due to the unavailability of species distribution maps for these groups in Norway. However, future analyses could incorporate other taxon groups and impact pathways as additional models and data become available. For example, the effects of water consumption on macro-invertebrates (Tendall et al., 2014).

Our assessment does not consider mitigation measures, potentially resulting in overestimating impacts. Modifications to water levels and the construction of artificial weirs contribute to reducing the pressure of hydropower plants on fish species in Norway (Helland et al., 2019; Miljødirektoratet, 2022; Sundt-Hansen et al., 2021). Studies have also shown that installing markers on power lines enhances wire visibility, reducing bird collisions (APLIC, 2012; Bernardino et al., 2018). Measures such as painting turbines black have also demonstrated a significant (70%) reduction in bird collisions (May et al., 2020b). Wind farms can further mitigate risks by adjusting turbine operations. For instance, changing speeds or shutting down during critical periods like bird migration (Marques et al., 2014; May et al., 2015). We excluded mitigation measures for two reasons. Firstly, mitigation measures were not integrated into the LCIA models we currently use. Secondly, extensive nationwide data on such measures in Norway are lacking, preventing their application in our analysis.

Numerous LCA studies underscore the benefits of low-carbon technologies (Gibon et al., 2017; Hertwich et al., 2015; Luderer et al., 2019; UNEP, 2016). Damage to ecosystem quality is commonly addressed through various impact pathways, such as climate change, ecotoxicity, eutrophication, water use, and land occupation (Crenna et al., 2020). Nevertheless, our findings indicate that direct land occupation (i.e., habitat loss) does not exclusively account for species loss. For example, direct habitat loss contributed less than half of the total impact of wind farms on bird diversity. This trend is similarly observed with power lines and bird richness, where collision posed a higher impact than direct habitat loss, underscoring the importance of developing models that quantify different drivers of biodiversity loss (Crenna et al., 2020; Damiani et al., 2023).

Notably, our study only assessed impacts within the area of protection of ecosystem quality. However, there are two more areas of protection within the LCA framework: human health and natural resources. While a shift towards decarbonising the energy sector may escalate pressure on ecosystems, it could significantly reduce pollution impacts on human health and mitigate climate change (Hellweg et al., 2023; Luderer et al., 2019).

Additionally, our analysis does not consider social aspects, although social acceptance is crucial for promoting energy production in Norway (NOU, 2023:3, 2023). Particularly, the construction of onshore wind farms caused social resistance in Norway, prompting the government to withhold concessions in 2019 for three years (NOU, 2023:3, 2023). While the Norwegian government resumed license processing for onshore wind farms (NOU, 2023:3, 2023; NVE, 2023c), the opposition against wind farms among Norwegians strengthened from 2018 to 2021 (CICERO, 2022).

Our study analyses the impacts of renewable energy production and transmission on biodiversity in Norway. The production, consumption, and transmission flow data were used to assess the distribution of the impacts within the pricing areas. While the electricity production data originated only from renewable sources, the share of renewables consumed or transmitted in each pricing area remained unknown. However, it is reasonable to assume that electricity distributed within Norway primarily comes from renewables, given that nearly all of Norway's electricity generation in 2022 was from renewables (NVE, 2021). In contrast, most of the electricity imported to Norway from Europe is derived from fossil thermal power, with less than a quarter sourced from renewables (NVE, 2021). Since we focused on assessing how impacts on Norwegian biodiversity are distributed across Norway, electricity import did not play an important role in our analysis.

To conduct the electricity network analysis, we established three assumptions: 1) electricity generated within a pricing area is primarily consumed locally, as the initial sale of electricity occurs within the pricing area (Statnett, 2021), 2) surplus electricity is transmitted to pricing areas experiencing a deficit (Statnett, 2021), 3) electricity is exported to Europe only when the electricity demand of Norwegian pricing areas is satisfied, as Norway can fulfil its domestic electricity needs (NVE, 2022). While our network analysis provided a sufficient basis for assessing how biodiversity impacts are distributed across the regions, it is important to note that it only offers a simplified overview of electricity data. We did not consider regional electricity prices, although they play a big role in the energy market (Statnett, 2023b). A further step could involve integrating our LCIA models with the TIMES-Norway model. Developed by the Institute for Energy Technology (IFE) and NVE, TIMES-Norway is an optimisation energy system model designed to encompass various factors such as energy demand across sectors, prices, resources, and electricity imports and exports (Danebergs et al., 2022). This model had previously been combined with LCA to evaluate the security of renewable energy (García-Gusano et al., 2017) and explore different energy policy scenarios (García-Gusano et al., 2016; Zhou et al., 2022).

While the impact occurs temporally and spatially in specific regions, the electricity demand may originate elsewhere. The shared contribution of European countries to the impacts on Norwegian biodiversity and Norway's dependence on electricity imports emphasise the interconnection of the European energy systems. Although nearly two-thirds of the electricity exchange between Norway and Europe is exported, a fair amount of electricity is imported (Statnett, 2023c). This supports the assertion that "No country is an energy island" (IEA, 2023) and highlights the need for a more comprehensive analysis that extends beyond national boundaries, embracing a European or global perspective.

The local distribution of production and consumption in Norway is spatially uneven, leading to disparate impacts on biodiversity throughout the country, with NO1 and NO3 exhibiting the most significant effects on species richness. As NO1 has a large energy deficit, the region relies heavily on imports (Statnett, 2023a), a dependence that is expected to intensify (NVE, 2022). The construction of new hydropower plants is primarily occurring in NO2 and NO5 (NVE, 2023g), while the development of onshore wind power is concentrated along coastal areas, primarily in regions NO2, NO3, and NO4 (NVE, 2023d). Moreover, further development of the capacity of the electric grid is underway, aiming to continue strengthening the network between north and south (Statnett, 2023b). While the electricity price difference varies greatly in Norway depending on the pricing areas, with a trend for higher electricity prices in southern Norway, biodiversity impacts are not factored into the price calculation. Instead, the focus remains on production capacity and electricity prices in neighbouring countries (Statnett, 2022b). However, biodiversity can significantly shape the cost-benefit distribution of power plants. For example, Grimsrud et al. (2023) demonstrated that northern Norway is most beneficial for future wind power development when considering areas of interest for wilderness and biodiversity.

Finally, our analysis is subjected to uncertainties, particularly in quantifying habitat loss associated with hydropower. Firstly, to assess the effect of land inundation and water consumption, we relied on the findings of three different studies (Dorber et al., 2018, 2019; Pierrat et al., 2023), each introducing its own set of uncertainties. Secondly, habitat loss attributed to the infrastructure of large-scale hydropower plants was based on data encompassing 70 hydropower plants and 105 reservoirs (Kenawi et al., 2023). Thirdly, quantifying habitat loss impacts from small-scale hydropower plants drew on data from 148 hydropower plants in Trøndelag, situated in central Norway (Hedger et al., submitted). These studies collectively cover only a fraction of the entire Norwegian hydropower system. Although the environmental effects of hydropower are site-specific (UNEP, 2016), we chose to use these studies to evaluate the nationwide impacts of hydropower plants. Given Norway's substantial dependence on hydropower, conducting a small-scale analysis would have led to a significant underestimation of our results. Our objective was to represent the overall biodiversity impacts of electricity production and transmission across pricing areas in Norway. This choice has, however, introduced a high uncertainty into our models, as evidenced by our sensitivity analyses.

5. Conclusions

The shift from fossil fuels to renewable energy sources is essential for mitigating climate change (Clarke et al., 2022). However, extending renewable energy production capacity and expanding the electric grid to connect new power sources with consumers will increase the pressure on species richness. LCA is a standardised tool for quantifying environmental impacts, identifying trade-offs across impact categories and analysing potential scenarios (Hellweg et al., 2023).

In our study, we combined and adapted available LCIA biodiversity models relevant to renewable energy production and transmission to assess the current effects of renewables on species richness in Norway. Our work presents the first comparable system-wide assessment of how the Norwegian renewable energy system affects biodiversity today. It compiles different impact pathways, covers three different taxonomic groups, and emphasises the importance of spatially explicit analyses when evaluating energy systems.

Since Norway is committed to expanding its energy capacity (KMD, 2021; NOU, 2023:3, 2023), our analysis can support future decision-making in planning the expansion of the Norwegian energy system. It can serve as a basis for developing electricity supply and demand scenarios and for assessing how constructing new energy facilities would affect biodiversity by identifying specific power plants and power lines responsible for high impacts. This could also be relevant for the review process of hydropower plant concessions, as it could highlight the specific impacts induced by each power plant and suggest initial favourable mitigation measures.

Solar power and offshore wind power will also contribute to Norway's future energy production (NOU, 2023:3, 2023; NVE, 2023c). New LCIA models that account for biodiversity impacts associated with offshore wind farms (Baulaz et al., in review; Critchley et al., in review) and solar power plants can be integrated into our analysis to enhance the holistic overview of the future Norwegian energy system.

Ultimately, while our analysis centres on Norway, our models can be readily adapted for application in other regions (either country or common market), provided the necessary input data are available, and the energy systems in place are based on hydro- and wind power production. It can also provide the basis for further expansion with the inclusion of impacts from other energy production sources (e.g., nuclear, biomass, geothermal).

CRediT authorship contribution statement

Dafna Gilad: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jan Borgelt:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Roel May:** Writing – review & editing, Supervision, Conceptualization. **Martin Dorber:** Writing – review & editing, Data curation. **Francesca Verones:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dafna Gilad reports financial support was provided by Research Council of Norway. Jan Borgelt reports was provided by Research Council of Norway. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the codes are available in a repository (see Supporting Information 2).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143096.

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