

Renewable energy growth amplifies land pressure on Norwegian biodiversity

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ABSTRACT

The rapid expansion of renewable energy is a key component in mitigating climate change. Although Norway generates most of its electricity from renewables, the country aims to increase its production to decarbonise sectors heavily reliant on fossil fuels. However, energy infrastructure requires land, and land change is a primary driver of biodiversity loss in Norway. A novel countryside species-area relationship model was applied to Norway's renewable energy infrastructure for future energy outlooks to derive potentially disappeared fractions of species. Habitat loss impacts on species richness were quantified for land-based technologies: hydropower (reservoirs and power plants), onshore wind, solar power, and power lines that traverse forests, excluding offshore wind. We modelled future biodiversity impacts based on projections from six scenarios that estimate electricity production through 2050 by renewable technologies in Norway. Our results suggest that while hydropower particularly affects birds and mammals due to habitat loss, future hydropower plants will have a smaller effect on species richness than onshore wind and solar power. The findings highlight that electricity production capacity and spatial location influence the magnitude of habitat loss impact on biodiversity. Therefore, prioritising projects with lower biodiversity impacts can mitigate the trade-offs between climate action and nature conservation. Our scenario analysis also indicates that the main driver of future pressure on biodiversity is not the strategic site selection of power plants but the overall demand for electricity production. By 2050, biodiversity impacts from habitat loss in Norway could increase by 16–28%, depending on the scale of renewable energy expansion.

1. Introduction

Norway is a global frontrunner in the transition to a low-carbon society. It ranks among the top countries for its high share of primary energy consumption from low-carbon technologies (Ritchie et al., 2024) and electric cars (Yang et al., 2023), deployment of the first operating electric ferry (Sjøtun, 2019) and development of offshore floating wind farms (Ibrion and Nejad, 2023). Yet two key measures remain essential for reducing Norway's greenhouse gas emissions: ensuring a large-scale integration of renewable energy sources (Malka et al., 2023) and implementing stringent policies to support the decarbonisation of fossil-based sectors (Zhou et al., 2022). Although Norway already has a high degree of electrification (IEA, 2022; NVE, 2023c), further decarbonisation across several sectors is essential to reduce greenhouse gas emissions (KLD, 2021). The need for decarbonisation is particularly true

for the industry, petroleum, and transport sectors (KLD, 2021; NOU 2023:3, 2023; OED, 2021). However, electrifying these three sectors alone could lead to an increase of 15–20 terawatt-hours (TWh) in electricity consumption by the end of this decade. By 2050, these sectors alongside new emerging industries such as, data centres and hydrogen production, are expected to jointly consume 59–89 TWh (NVE, 2025; Statnett, 2025), as the Norwegian government aims to further decrease emissions by 90% compared to 1990 levels (KLD, 2021). Therefore, an increase in electrification necessitates an expansion of renewable electricity production (KLD, 2021; NOU 2023:3, 2023).

Norway already generates most of its electricity from renewable sources, primarily hydropower (SSB, 2024a). Yet, most viable hydropower resources have already been developed, and much of the remaining potential is now under environmental protection (ED, 2021; NVE, 2020). Therefore, future projections for hydropower focus on

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upgrading and expanding existing hydropower plants (DNV, 2024; NVE, 2025). As a result, the focus of future electricity production is expected to shift towards wind and solar power (NVE, 2025; Statnett, 2025), which are emerging as the leading renewable technologies worldwide (IEA, 2023). In addition to power generation, power lines must be upgraded and expanded to ensure a high transmission capacity (DNV, 2024; NOU 2022:6, 2022; Statnett, 2025). However, the expansion of energy generation and transmission infrastructure requires land to operate.

Land use change is one of the major global drivers of biodiversity loss (IPBES, 2019), and Norway is no exception. Habitat change affects nearly all threatened species in Norway, with nine out of ten species at risk due to land use changes (Artsdatabanken, 2021b). Yet Norwegian natural habitats are constantly being degraded. Between 2017 and 2022, 44,000 incidents of nature degradation were caused by construction across Norway, indicating a loss of 207 km² of natural habitats (Støstad et al., 2024). Furthermore, energy infrastructure, especially hydropower, onshore wind, and power lines, has become the main contributor of unspoiled nature loss in Norway over the last 10–15 years. In the past five years alone, energy development has led to approximately 60% reduction of unspoiled nature (Miljødirektoratet, 2024). In Norway, future infrastructure development is largely planned within natural habitats, particularly forests (Simensen et al., 2023). The future expansion of renewable facilities may therefore come at a cost to Norwegian nature.

A recent study evaluated the overall biodiversity impacts of the current installed Norwegian electricity system, focusing on the impacts of hydropower, onshore wind power, and power lines (Gilad et al., 2024a). We built upon this study to analyse Norway’s future energy infrastructure. We developed a novel, national, and technology-consistent countryside species-area relationship (c-SAR) framework tied to actual planned assets and contrasted across six independent energy outlooks for future development. This is valuable for near-term energy planning in Norway, as it explicitly allocates impacts to assets and provides a per-GWh comparison, serving as actionable levers for siting and prioritisation. Our analysis includes hydropower plants, onshore wind farms, and solar power plants planned to be constructed by 2050. Offshore wind installations were not included in the analysis, as we focused solely on the impacts of terrestrial habitat loss.

2. Methodology

We conducted a spatial analysis, mapping 13 habitats, species richness of four taxonomical groups, and renewable energy infrastructure across Norwegian landscape subregions. By estimating habitat

suitability and the areal footprint of operational and planned power plants, we used species-area relationship (SAR) models to quantify biodiversity impacts from habitat loss caused by renewable energy infrastructure in Norway. To assess how future development may affect biodiversity, we modelled six future scenarios of projected future electricity production: three based on Norwegian reports and three assuming the dominance of a single technology (i.e., hydropower, onshore wind, or solar power) (see Fig. 1).

2.1. Species-area-relationship

We quantified the impacts of habitat loss due to electricity infrastructure using SAR. The SAR is a well-established ecological concept that describes how habitat size influences the number of species it can sustain (Rosenzweig, 1995). The SAR concept suggests that a reduction in habitat area will lead to a decline in species richness. It has been frequently used to quantify the impacts of land use on biodiversity (Chaudhary and Brooks, 2018; May et al., 2020; Pereira et al., 2014). In our analysis, we used the c-SAR (i.e., countryside SAR) (Pereira et al., 2014), which incorporates species’ habitat suitability for different habitat types. The c-SAR quantifies the total impact of a given landscape configuration in relation to a reference state (i.e., landscapes without energy infrastructure), which is henceforth allocated to individual land types (Kuipers et al., 2021). To quantify the impacts of electricity infrastructure, we treated each infrastructure item, i.e., individual power plants, hydropower reservoirs, and the power line network including pylons, as an individual habitat type (see section 2.2.5). We consider the Norwegian landscape without electricity infrastructure as the reference state.

The resulting biodiversity impacts are quantified as the Potentially Disappeared Fraction of species (PDF) of a taxon within a given region. The PDF is a common and recommended metric for describing biodiversity impacts within the framework of life cycle assessment (Verones et al., 2017). It is assessed by comparing the sum of habitat suitability (h) of habitat type i to taxon g multiplied with the area size (A) of all habitat types in region j in its current state versus a reference (ref) state, raised to the power of z (Eq. 1). The z-value is a constant representing the slope of the SAR. We applied Eurasian z-values from Storch et al. (2012) and an averaged z-value across Norwegian biomes from Gerstner et al. (2014) (see Table S1, Supporting Information 1).

$$PDF_{g,j,regional} = 1 - \left(\frac{\sum_i h_{g,i,j} A_{i,j}}{\sum_i h_{g,i,j} A_{i,j,ref}} \right)^{z_{g,j}} \quad (\text{Eq. 1})$$

The habitat suitability (h) is defined as the number of species (S) of taxon g present in habitat type i in region j in relation to the total number

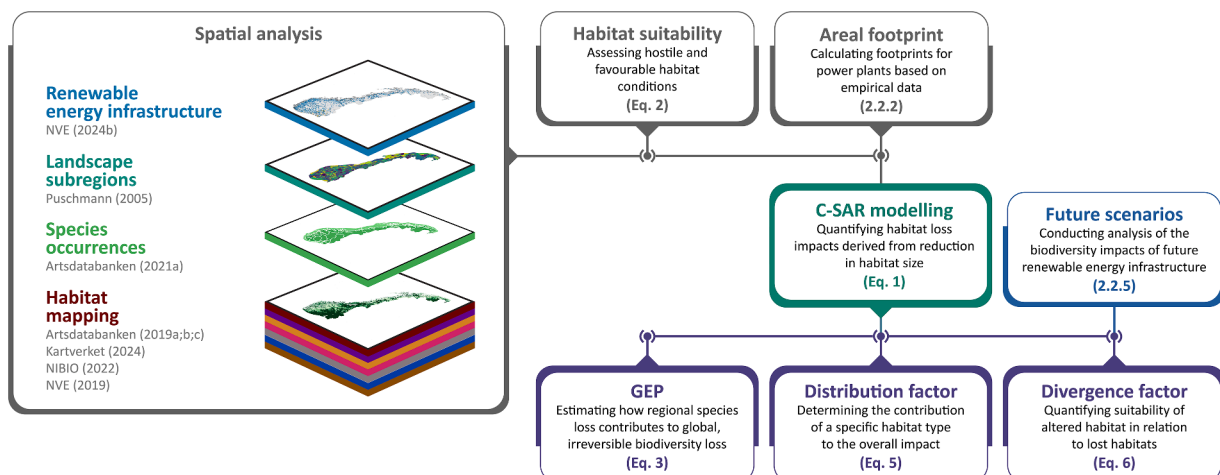


Fig. 1. The outline of the study’s methodological approach.

of species of taxon g within region j , raised to the power of $1/z_g$ (Eq. (2)). Habitat suitability values were calculated for all the natural and anthropogenic habitat types. Habitat suitability values vary from 0 to 1, with lower values indicating a hostile habitat while higher values represent favourable habitat conditions.

$$h_{g,i,j} = \frac{S_{g,i,j}^{1/z_g}}{S_{g,j}} \quad (\text{Eq. 2})$$

Since the regional disappearance of species does not provide an indication of severity for the global persistence of biodiversity, we converted the assessed PDF of taxon g in region j to a global species loss using the global extinction probability (GEP) (Eq. (3)). The GEP estimates how species loss within a local region can affect global species loss, based on species richness, range sizes, and conservation status (Kuipers et al., 2019). The GEP for taxon g in region j was quantified by summing the values at the pixel level that fall within a given region (Verones et al., 2022). The GEP effectively describes the contribution of a regional species loss to the global irreversible loss of species from taxon g .

$$PDF_{g,j,global} = PDF_{g,j,regional} \times GEP_{g,j} \quad (\text{Eq. 3})$$

As habitat change may not always have negative effects and can even benefit some species (i.e., converting forest to open habitat), we allocated biodiversity impacts based on landscape configuration. First, we assessed the contribution of habitat type i to the overall impact by multiplying a distribution factor (q) by the quantified impact on taxon g in region j (Eq. (4)).

$$PDF_{g,i,j} = PDF_{g,j,global} \times q_{g,i,exp,j} \quad (\text{Eq. 4})$$

The distribution factor q is affected by two aspects: the areal gain (A) of expanding habitat type i_{exp} and a divergence factor (δ) (Eq. (5)).

$$q_{g,i,exp,j} = \frac{A_{i_{exp},j} \times \delta_{i_{exp},j}}{\sum_{i_{exp}} A_{i_{exp},j} \times \delta_{i_{exp},j}} \quad (\text{Eq. 5})$$

The divergence factor δ describes the difference between the suitability of the expanding habitat type i_{exp} and the average suitability across all habitat types that were lost i_{lost} in region j for species of taxon g (Eq. (6)).

$$\delta_{g,i,exp,j} = h_{g,i,exp,j} - \bar{h}_{g,i_{lost},ref} = h_{g,i,exp,j} - \frac{\sum_i h_{g,i_{lost},j} A_{i_{lost},j,ref}}{\sum_i A_{i_{lost},j,ref}} \quad (\text{Eq. 6})$$

The distribution factor can be positive or negative, depending on whether the gained area is more or less suitable than the lost area. This approach allows individual habitat types i to contribute positively or negatively to the total impact on taxon g in region j . Increasing the extent of habitat types with lower suitability than the average of lost habitat types would therefore result in negative effects, and vice versa. The distribution factor (q) is used to allocate the biodiversity impacts, positive or negative, on taxon g due to the landscape configuration in region j to all contributing habitat types i_{exp} .

2.2. Spatial analysis

We calculated the habitat loss impacts at the landscape subregion level as a regional alternative to global ecoregions. Ecoregions are a commonly used spatial unit in biogeographical analyses (Kuipers et al., 2019; Scherer et al., 2023). These spatial units aim to represent large spatial areas characterised by similar species compositions. Yet only six out of 825 global ecoregions encompass parts of Norway (Olson et al., 2001), which offers a very coarse characterisation of the country.

The Norwegian landscape subregions ($n = 446$) were developed specifically for Norway on a county level, yet they do not necessarily align with administrative borders but focus on landscape features. They are defined by six features: major landforms, geological composition, water bodies and waterways, vegetation patterns, agricultural areas,

and built infrastructure (Puschmann, 2005). Thereby, providing a suitable alternative regional spatial unit to global ecoregions.

We calculated the total area of each habitat type within every landscape subregion. This represented the reference state since electricity infrastructure was not included in land cover datasets (see Section 2.2.3). We used three landscape configurations: 1) reference state: the original landscape without electricity infrastructure, 2) operational infrastructure: a landscape configuration including existing infrastructure in 2024 (i.e., power plants, power lines, pylons, and reservoirs), and 3) future infrastructure: a landscape configuration where both operational and planned power plants are incorporated.

At each location of an operational or planned power plant, pylon, power line corridor, or reservoir, we replaced the existing habitat type with a new habitat type called “power plant”, “pylon”, “power line corridor”, or “reservoir” (see Fig. 2). We identified the number of species present in each habitat type within a landscape subregion to assess how habitat suitability is affected by the development of electricity infrastructure (see 2.2.3). The impacts of the current electricity system were assessed by comparing the reference state (landscape configuration 1) with the operational infrastructure state (landscape configuration 2). The impacts of future power plants were quantified by comparing the landscape configurations of the operational infrastructure (2) with the future infrastructure (3).

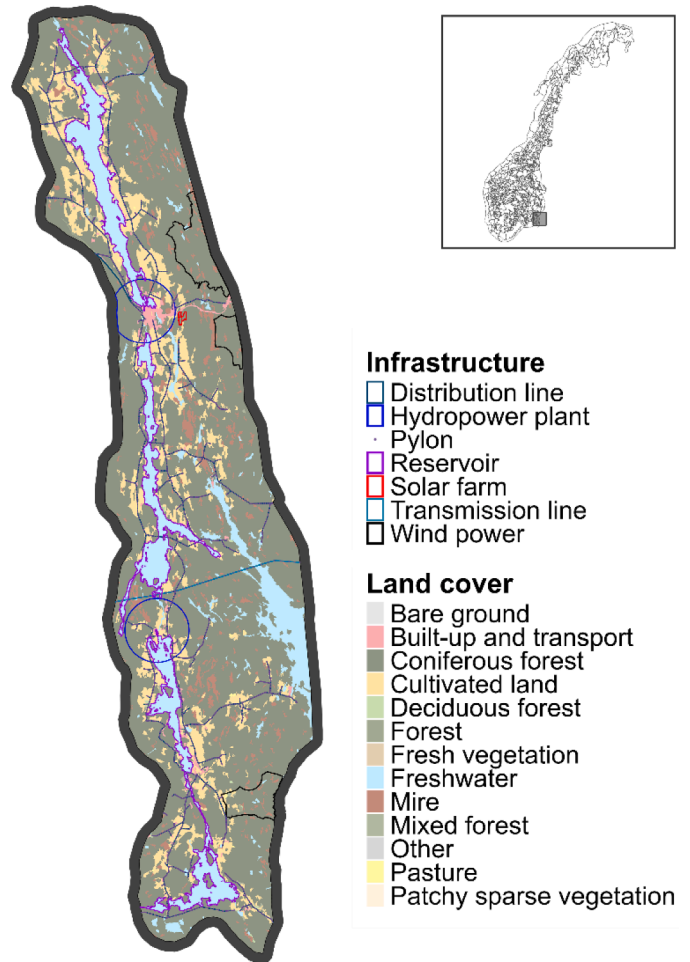


Fig. 2. Landscape configuration in subregion 6.1 (landscape subregion 29 in Table S9, Supporting Information 1), showing electricity infrastructure overlaid on land cover mapping (NIBIO, 2022). The top-right inset map, indicates the subregion’s location within Norway, highlighted by a grey box.

2.2.1. Mapping operational and planned electricity facilities

All geodata of electricity facilities were obtained from the Norwegian Water Resources and Energy Directorate (Noregs vassdrags- og energidirektorat; NVE) (NVE, 2024b). Power plant data of hydropower ($n = 3315$), onshore wind ($n = 224$), and solar power ($n = 61$) and reservoir data ($n = 1514$) were downloaded on October 16, 2024. Power line (ca. 90,000 km) and pylon ($n = 650,845$) data were obtained on August 14, 2024, including both transmission and distribution lines. NVE's datasets include planned energy facilities in addition to existing ones. However, the datasets did not include direct footprint information. Based on existing studies (Dorber et al., 2018; Gilad et al., 2024b; Hedger et al., 2025; Kenawi et al., 2023; NVE, 2023a; Ong et al., 2013), we estimated habitat loss for existing and planned power plants by adjusting the direct area loss of each respective energy source, i.e., hydropower, onshore wind, and solar, as described in Supporting Information 2.

The exact area losses from power plants affect the magnitude of the impact, which introduces uncertainty. Consequently, we conducted a sensitivity analysis by generating multiple areal loss estimations and their respective biodiversity impacts per technology across 500 iterations to demonstrate how variations in estimated areal losses can affect the impacts. Additional sensitivity analyses were conducted for hydropower power plants: since the geodata did not contain information about the exact location of areal losses, we created a buffer of 2000 m around each power plant point location and assumed the footprint area would occur within that buffer (see Supporting Information 2). We tested sensitivity by using a one-at-a-time approach: 1) varying buffer radius (500, 1000, 2000, and 4000 m) while holding the C-SAR exponent constant, and 2) varying the C-SAR exponent (z-values reduced or increased by 20 %) while holding buffer radius constant at 2000 m. For each parameter combination, biodiversity impacts were recalculated and compared to the baseline scenario: 2000 m buffer and no increase or decrease in z-values. Sensitivity was evaluated in terms of both changes in PDF magnitude and the stability of facility and technology rankings, the latter quantified using Spearman rank correlations relative to the baseline scenario.

2.2.2. Mapping species occurrences

Species occurrence data were obtained from the Norwegian Red List (2021 Version) (Artsdatabanken, 2021a). The analysis focused on four taxa: birds, herpetofauna (i.e., amphibians and reptiles), mammals, and vascular plants, comprising 217, eight, 50, and 769 species, respectively. Amphibians and reptiles were aggregated into one taxonomic group, as they are grouped together in the Norwegian Red List.

The Norwegian Red List documents species presence across 17 mainland geographic regions in Norway. The six additional island regions were excluded. Species occurrence data were available for each geographic region, with only "known occurrence" considered as an indicator for species presence. These geographic regions are based on the boundaries of historic administrative counties, totalling 17 counties (Artsdatabanken, 2021a).

2.2.3. Mapping habitats

In addition to information on the geographical distribution of species, the Norwegian Red List provides details about their preferred habitats out of 13 different habitat types in Norway: arctic, rock and scree, freshwater, intertidal zone, alpine, floodplain, snow and ice, coast, saltwater, semi-natural, forest, highly modified, and wetland. Habitat classifications in the Norwegian Red List are based on Nature in Norway (NiN), a conceptual framework developed to classify Norwegian ecosystems (Artsdatabanken, 2023). However, NiN is not yet mapped out throughout Norway. The habitat types were, therefore, matched to available land cover information to assess the present species, and, hence, the habitat suitability, within each subregion. We combined a range of land cover maps to match each land cover type to a given habitat type, including data on the location of the tree line (Version 2019) (Artsdatabanken, 2019c), sea level (Version 20240220)

(Kartverket, 2024), outlined areas characterized by coastal conditions (Version 2019) (Artsdatabanken, 2019a), wetlands (Version 2019) (Artsdatabanken, 2019b), regular floods (Version 11.01.2019) (NVE, 2019a), and basic land cover data (Version 20220523) (NIBIO, 2022). For more information, refer to Table S7 in Supporting Information 1.

In each landscape subregion, we assigned a habitat suitability (h) value to each existing land cover type (see Section 2.1, Eq. (2)). Here, we counted the number of species present based on the spatial overlap of the subregions with the 17 Norwegian counties and their preferred habitat within the counties (see Supporting Information 1, S8-S9). For example, the Golden Eagle (*Aquila chrysaetos*) is found throughout most of Norway except for two counties in the southeast of Norway. Within the given counties it is present, the Golden Eagle inhabits forests and alpine areas (Artsdatabanken, 2021a).

The habitat suitability of electricity infrastructure (i.e., power plants or pylons) was considered equal to that of "highly modified", reservoirs were considered as "freshwater" habitats, and for power line corridors, we assumed the new habitat suitability matched that of "semi-natural". Approximately 56 % of Norwegian power lines intersect forest habitats. As power line corridors require vegetation removal (i.e., tall trees) during construction and operation to reduce risk for the infrastructure (Biasotto and Kindel, 2018; Richardson et al., 2017), we confined habitat loss of power line corridors to forest habitats. Therefore, only power line corridors in forest land cover types were considered to shift to "semi-natural". If power lines crossed non-forest habitats, only the areal footprint of the pylons was considered as habitat loss. We assigned the pylon footprint areas a habitat suitability equal to that of a "highly modified" habitat.

2.3. Future production scenarios

We examined six different scenarios: three report-based and three technology-based. Each scenario was divided into three milestones by decade: 2030, 2040, and 2050. For each milestone, we calculated the additional electricity needed by subtracting the current production capacity from the total projected output for that milestone. The calculations were done separately for each technology, excluding offshore wind, as we focus on impacts related to land use. These projections served as thresholds for electricity that each technology was expected to produce at each milestone. In each of the 500 iterations of estimating impacts, the power plants needed to meet these thresholds were selected randomly using Monte Carlo draws over 100 iterations (a total of 50,000 iterations). As the data on planned power plants are insufficient to meet all targets, we allowed a repeated sampling of planned power plants when necessary to reach the scenario targets. In each iteration, we randomly selected new capacity (i.e., only planned power plants) to achieve the scenario-specific targets and multiplied the added electricity by this factor to estimate incremental power line impacts.

Because spatially explicit routing and commissioning data for future transmission infrastructure are unavailable, we allocate transmission-related biodiversity pressure to future electricity additions using a national-average intensity derived from the observed system (PDF per GWh). This corresponds to a base assumption ($\alpha = 1.0$) in which marginal transmission impacts scale linearly with added electricity generation. To bound this linear scaling assumption, we introduce a corridor re-use sensitivity case in which a large share of future transmission capacity is achieved within existing power line corridors (e.g., via reconductoring or upgrading of existing lines), rather than through construction of new corridors. This is implemented by scaling the marginal post-2023 transmission impact by a factor $\alpha = 0.2$ relative to the base intensity. This value represents a conservative lower-bound scenario motivated by evidence that advanced conductors and grid-enhancing technologies can approximately double transfer capacity within existing corridors and supply a substantial share of near-term transmission expansion (Chojkiewicz et al., 2024). We therefore interpret $\alpha = 1.0$ as a proportional buildout at historical average intensity,

and $\alpha = 0.2$ as a corridor re-use bound reflecting predominantly within-corridor reinforcement. Results are reported for both cases to illustrate how assumptions about future grid routing affect absolute biodiversity pressure. Scenario comparisons (i.e., report- and technology-based) are based on generation-related impacts to avoid obscuring differences driven by technology mix.

All data analyses were performed using R version 4.4.0 (R Core Team, 2024) in RStudio version 2024.04.1 + 748.

2.3.1. Report-based scenarios

We obtained future production data from three Norwegian companies and institutes to model the future potential biodiversity impacts: The Norwegian Veritas (Det Norske Veritas; DNV), a company that works with assurance and risk management (DNV, 2024), NVE (NVE, 2025), and Statnett (Statnett, 2025), the system operator of the Norwegian national grid. Each dataset projects the amount of renewable electricity (GWh or TWh) expected in Norway up to 2050 from hydropower, onshore wind, and solar power (see Table 1).

DNV. The DNV data provide annual estimates from 2023 to 2050. Its projection suggests that since hydropower has limited potential to expand, its future focus will be upgrading existing facilities. DNV’s report suggests wind power as the only realistic technology to produce large additional amounts of electricity, growing strongly during the 2030s. As solar power is the cheapest technology, it is expected to expand in the second half of the 2020s. Solar power predictions were divided into two categories: solar power and solar power combined with storage facilities. We assumed that storage facilities would be built for both rooftop and ground-mounted solar projects, with a 1:1 ratio. Therefore, we summed the projected solar production with and without storage, and then halved the total, assuming that 50 % of solar generation would originate from ground-mounted projects. As NVE and Statnett scenarios do not distinguish between rooftop and ground-mounted projects, or between installations with and without storage, we applied the same 1:1 ratio to their solar production projections.

NVE. The electricity projection data from NVE (Version basis LA25) cover 2022, 2030, 2035, 2040, and 2050. NVE also assumes a large development in wind power, with most of the development occurring between 2030 and 2040. Although there is a great potential for offshore wind deployment in Norway, predictions for electricity production remain conservative and uncertainty since this technology is highly depended on subsidies. As the demand for solar panels on rooftops dropped since 2024, NVE expects slow growth for solar power, as its development requires legal frameworks and incentives. While there is great interest in deploying ground-mounted projects in Norway, limited grid capacity and administrative barriers might hinder rapid development. The growth in electricity production by hydropower would be based on new plants and the expansion of existing projects. New turbines are presumed to be replaced in many hydropower plants, which could increase efficiency in electricity generation. Furthermore, since the water inflow to hydropower plants has increased in recent decades, NVE expects the inflow to further increase in the upcoming years, which may result in a slight growth in hydropower production.

Statnett. Statnett’s data project annual average TWh production estimations for 2022, 2030, 2035, 2040, and 2050 (Version basis LMA 2024). Statnett assumes an increase in the flexibility of hydropower

through better capacity of existing plants and the development of pumped storage power plants. Onshore and offshore wind projects are expected to grow from 2035 onwards and contribute most to cover the increasing electricity demand. Solar power development is projected to grow gradually over the years.

2.3.2. Technology-based scenarios

To demonstrate the potential habitat loss effects of the technologies on biodiversity, we also modelled technology-based expansions, relying on existing reports. We calculated the average projections of electricity production per milestone based on the DNV, NVE, and Statnett scenarios. Then we created scenarios per technology, aiming to maximise the production of a single technology per scenario while relying on its given potential expansions (see Table 2).

Hydropower. We assigned hydropower the highest projected values across the DNV, NVE, and Statnett reports, while solar and onshore wind were given the lowest values. Since all three report-based scenarios assume only a minor expansion of hydropower, we increased the maximum hydropower production projections by eight TWh to meet the 2040’s milestone, based on the estimated potential for small-scale hydropower development (NOU 2023:3, 2023). An additional of 17 TWh was added to the maximum values for the 2050 milestone, reflecting the potential for hydropower development in protected watersheds (NVE, 2020). We reduced the minimum onshore wind values to maintain the dominance of hydropower and to ensure a more balanced contribution between onshore wind and solar power.

Onshore wind. Similarly to the hydropower scenario, maximum values for onshore wind were extracted from the existing reports per milestone. Minimum values were assigned to hydropower and solar power and were slightly increased where necessary to ensure a balanced contribution between the two technologies. As the 2050 milestone can be achieved through onshore wind projections alone, values across all technologies were adjusted to reflect the dominance of onshore wind while maintaining a balanced contribution between hydropower and solar power.

Solar power. To achieve high solar power projections, we discarded the 1:1 ratio (see Section 2.3.1) and assigned maximum values to solar power. The projections were further increased for the two latter milestones: by an additional one TWh in 2040 and four TWh in 2050, ensuring it is within the estimated potential for ground-mounted solar projects in already developed areas, parking lots, and agricultural land (Multiconsult, 2022). Hydropower and onshore wind were assigned minimum projected values across the milestones, with minor adjustments as required to maintain balance between the two technologies and to meet each milestone.

3. Results

3.1. Area loss across habitats

Energy infrastructure development has led to area loss across all terrestrial Norwegian habitats (see Figure S1 in Supporting Information 2). The most affected habitats by operational renewable projects are floodplain, mountain, arctic and forest habitats, while intertidal, snow and ice areas experienced the least area loss. Across technologies,

Table 1

Total expected electricity production across the three scenarios, quantified in TWh (rounded), and presented for the three milestones 2030, 2040, and 2050 (see Table S11 in Supporting Information 1).

	2030			2040			2050		
	DNV	NVE	Statnett	DNV	NVE	Statnett	DNV	NVE	Statnett
Hydropower	141	142.3	143	139	146	146	143	147	148.4
Onshore wind	14	16.1	17	27.4	29	23	50	33	27.8
Solar power	1	1.2	2	3.3	4	4	9.5	5	7.3
Total	156	160	162	170	179	173	202	185	184

Table 2

Electricity expansion potential across the three technology-based scenarios, quantified in TWh, and presented for the three milestones 2030, 2040, and 2050 (see Table S11 in Supporting Information 1).

	2030			2040			2050		
	Max hydro	Max wind	Max solar	Max hydro	Max wind	Max solar	Max hydro	Max wind	Max solar
Hydro-power	143	142	141	153	142	144	165	143	146
Onshore wind	15	16	15	18	29	20	20	44	21
Solar power	1	1	3	3	3	10	5	3	23
Total	159			174			190		

operational hydropower reservoirs accounted for the largest area loss, affecting floodplains, mountains, arctic regions, and forests. Power lines also had a large effect on Norwegian habitats: forests experienced the greatest habitat loss due to the establishment of power line corridors, followed by arctic and semi-natural habitats. As pylons have a relatively small footprint, they only led to a small habitat loss, yet as power lines, they affected mostly forests, arctic regions, and semi-natural habitats. Operational and planned hydropower plants affect primarily forests, semi-natural, mountains, and floodplains, yet on a much smaller scale when compared to hydropower reservoirs. Operational solar plants and onshore wind caused a minimal area loss in Norwegian habitats. Operational onshore wind farms particularly affect wetland, semi-natural, and coastal habitats. However, if planned projects are to be constructed, onshore wind farms can lead to significant area loss in mountains, arctic, and semi-natural regions. Future solar power plants are planned to be built mostly in forests (see Fig. 3 and Tables S2-S6, Supporting Information 1).

Regarding species richness, semi-natural and forest habitats are the most species-rich habitats across the four taxonomical groups. Many species also inhabit coastal habitats, rock and scree, and wetlands, while snow, ice, and arctic regions are home to a small number of species (see Table S8 in Supporting Information S1).

3.2. Biodiversity impacts of operational and planned renewable infrastructure

On average, reservoirs had the largest footprint, followed by operational onshore wind farms and hydropower plants. The area lost by operational solar power farms remains very small. In the future, the

average footprint of hydropower plants will potentially decrease because the planned hydropower plants are mostly small-scale projects. Planned solar power and onshore wind plants will have a larger footprint compared to operational projects, as new facilities will produce, on average, more electricity than the current operational projects (see Supporting Information 1, Tables S2-S5 and Figure S2 in Supporting Information 2).

Across technologies and taxa, hydropower reservoirs were the largest contributor to current terrestrial habitat loss, followed by power line corridors, hydropower plants, onshore wind farms, and solar power plants. However, our findings suggest a potential for further habitat loss in the future due to the construction of onshore wind power and additional hydropower plants. Overall, solar power plants are expected to have the least additional habitat loss impact (see Figure S5 in Supporting Information 2). Yet, when considering the relative effect of each power plant by dividing its impact value by its electricity production capacity (i.e., PDF/GWh), solar plants would have on average the highest biodiversity impact per GWh produced, as they produce the least amount of electricity compared to the other technologies. Operational and planned hydropower plants have the least relative impact on biodiversity per GWh across the three technologies. Overall, the relative biodiversity impacts (PDF/GWh) of onshore wind farms are expected to decrease somewhat for planned projects, potentially due to higher production capacity and site selection (see Fig. 4 and Tables S2-S4, Supporting Information 1).

Planned hydropower plants are expected to affect biodiversity across the country, mostly in southwestern Norway. Potential onshore wind farms are projected to concentrate along the southwest coast of Norway, as most of them are coastal. Future solar power plants are planned to be

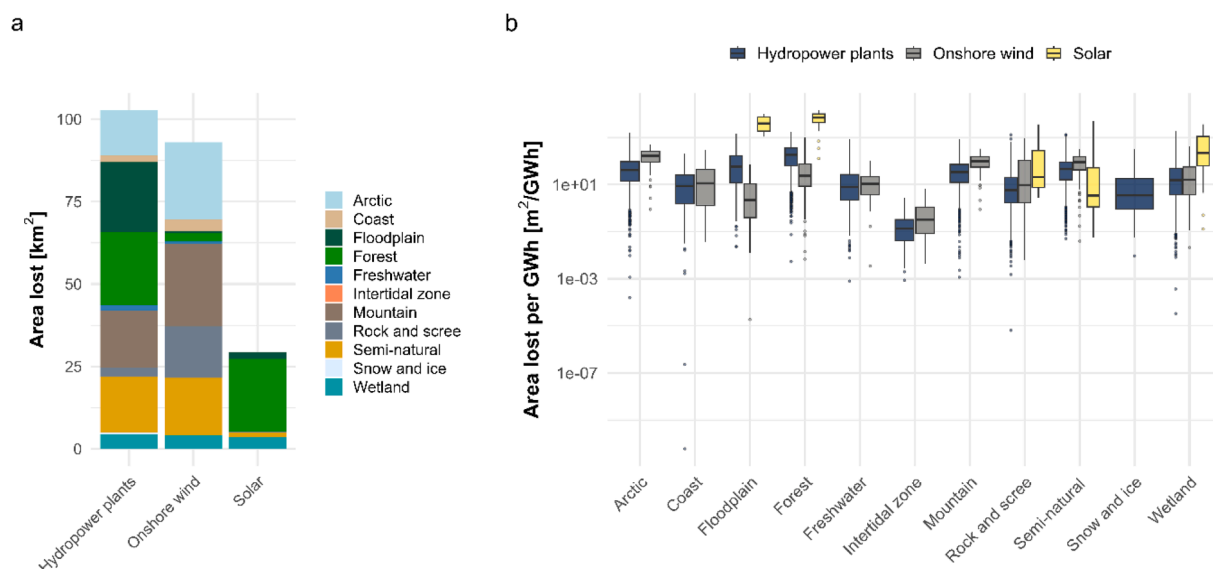


Fig. 3. (a) Area loss (km²) across Norwegian habitats due to the development of planned renewable infrastructure: hydropower plants, onshore wind, and solar power plants. (b) Areal footprint per unit of electricity generation (m²/GWh, at the log₁₀ scale) across habitats and technologies, showing variability among individual planned power plants. Boxplots display median, interquartile range, and outliers, with points representing individual plant-level means (averaged across simulation iterations).

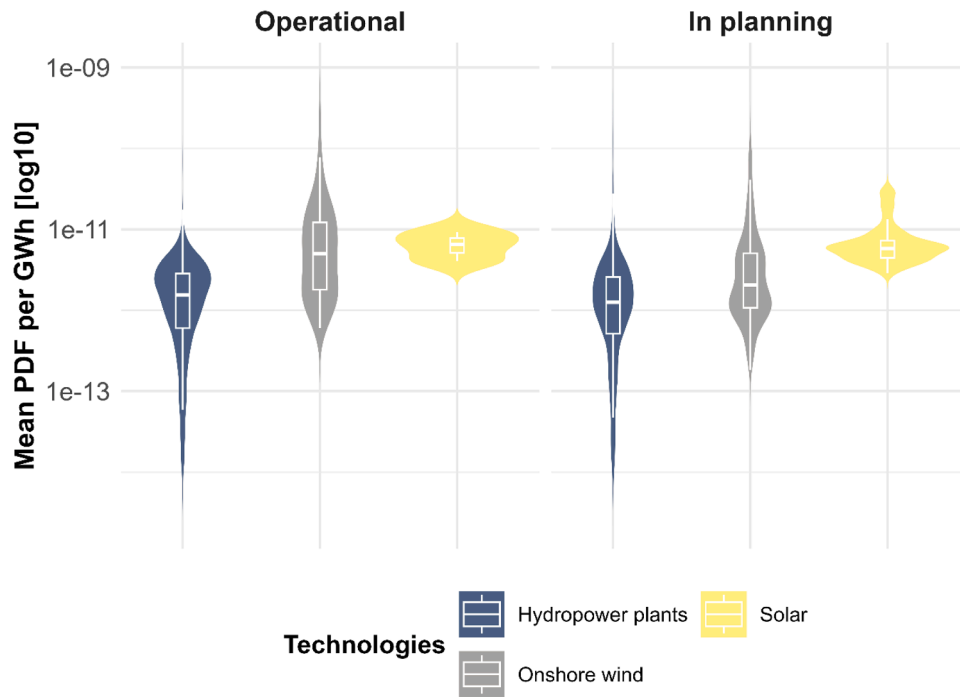


Fig. 4. Biodiversity impacts (PDF) per GWh (\log_{10}) produced by operational renewable energy projects in Norway (left) and of planned facilities (right), categorised into the different technologies from left to right: hydropower plants (blue), onshore wind (grey), and solar (yellow).

built primarily in the southeast of the country (see Fig. 5).

Hydropower reservoirs and plants, and onshore wind farms impact all taxa, particularly birds and mammals. Herpetofauna were the least affected by habitat loss from energy infrastructure. Most of the habitat loss impact is due to land inundation to establish hydropower reservoirs. Habitat loss caused by onshore wind farms remains small, while solar power has a marginal effect compared to all other technologies. Power lines (aggregated with pylons) negatively affect birds and mammals but also demonstrate some positive effects on vascular plants and herpetofauna, as presented in Fig. 6 by the negative PDF values (see Table S12 in Supporting Information 1).

The relative impact of each power plant (PDF/GWh) highlights which power plants are efficient in producing electricity with a low impact on biodiversity. The relative biodiversity impact is not determined necessarily by the technology itself or production capacity, but also by the siting of single projects, identifying planned individual projects with relatively high or low biodiversity impacts (Fig. 7).

Sensitivity analyses for hydropower plants indicated that absolute

PDF estimates showed some sensitivity to model assumptions, whereas relative rankings were highly robust. When varying buffer size while holding the C-SAR exponent fixed at its default value (z), median PDF estimates differed by -1.9% to 1.4% relative to the baseline buffer (2000 m), with 5-95% quantiles spanning -31.4% to 44.6% (Table S13). Uncertainty in the C-SAR exponent had a larger effect on absolute magnitude: when varying z -values while holding buffer size fixed at 2000 m, median PDF estimates differed by -21.4% to 20.5% relative to the baseline z value, with 5-95% quantiles spanning -30% to 32% (Table S14).

Despite these changes in absolute magnitude, the ranking of individual facilities by total PDF was highly stable across all sensitivity scenarios. Spearman rank correlations between plant-level PDF rankings obtained under alternative buffer sizes and the baseline scenario ranged from $\rho = 0.99$ to 1. Rankings obtained under alternative z -values were identical to the baseline ranking ($\rho = 1$ throughout).

Overall, these results indicate that while absolute impact estimates vary with assumptions about buffer extent and C-SAR parameterization,

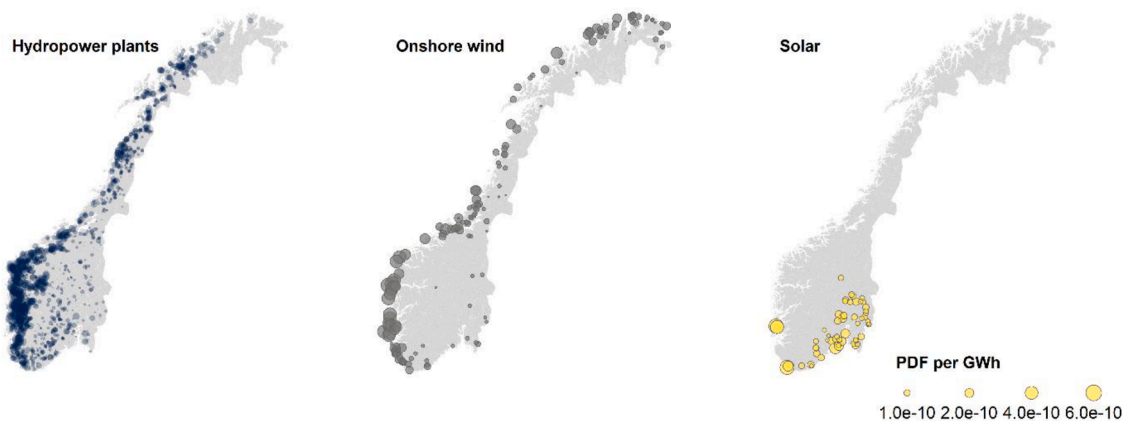


Fig. 5. Biodiversity impacts (PDF per GWh produced) for planned power plants across three renewable energy technologies: hydropower plants (left, blue), onshore wind (centre, grey), and solar power (right, yellow). The circle sizes represent the relative magnitude of biodiversity impacts.

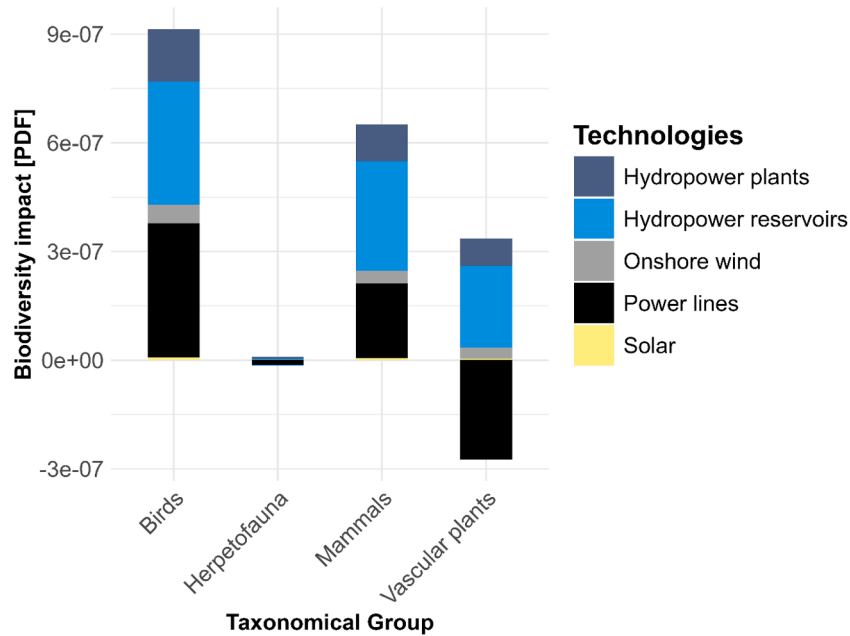


Fig. 6. Biodiversity impacts of operational and planned hydropower plants (blue), hydropower reservoirs (bright blue), onshore wind (grey), power lines (black), and solar (yellow) on four taxonomic groups: birds, herpetofauna, mammals, and vascular plants. The bars represent the overall habitat loss effects of renewable energy on biodiversity in Norway. See Figure S5 in Supporting Information 2 for separated results for operational and planned projects.

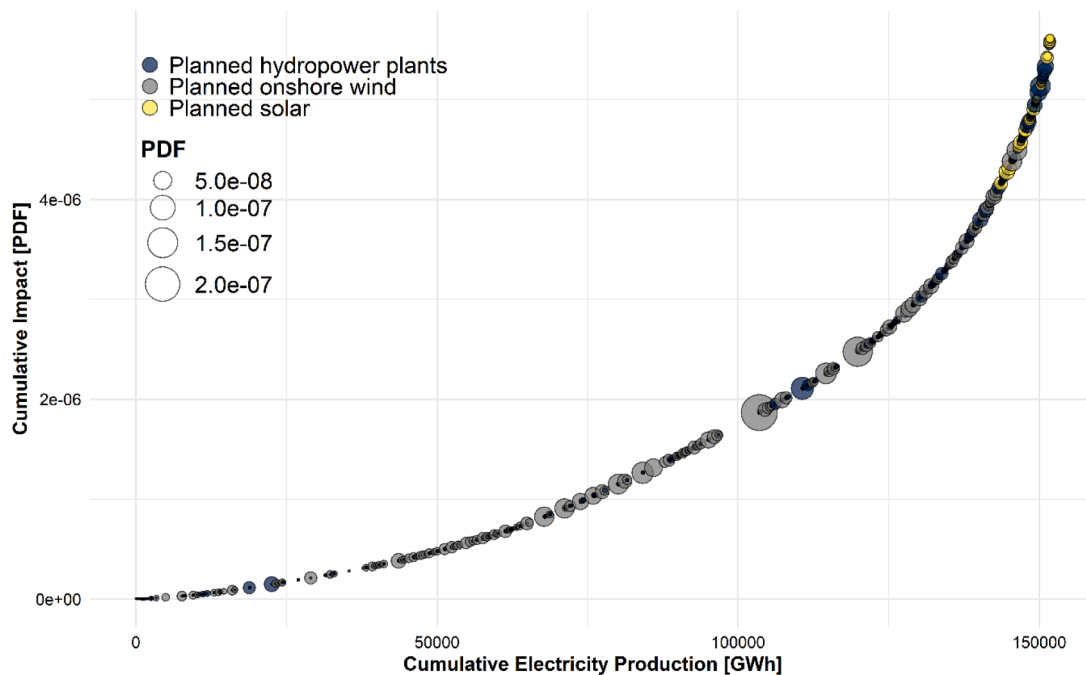


Fig. 7. The cumulative biodiversity impact (PDF) and electricity production (GWh) for only planned power plants are sorted by relative impact (PDF/GWh). The circle sizes represent the total impact (PDF) of each individual power plant. Hydropower plants are indicated in blue, onshore wind farms in grey, and solar power plants in yellow.

conclusions regarding the relative importance of individual facilities and technologies are robust to plausible parameter uncertainty.

3.3. Future scenarios

The six scenarios present varying outcomes for biodiversity impacts, closely tied to the projected amounts of renewable electricity production (see Fig. 8 and Figures S6-7 in Supporting Information 2). The Statnett

scenario initially demonstrates the highest biodiversity impact in 2030, yet projects lower impacts by 2040 in comparison to DNV and NVE scenarios. By 2050, its impacts level out with those of NVE scenario. The DNV scenario accelerates slowly and is associated with lower biodiversity impacts compared to the NVE and Statnett scenarios. However, since the DNV scenario forecasts the largest growth in electricity production by 2050, it also anticipates a substantial rise in overall biodiversity impacts by 2050.

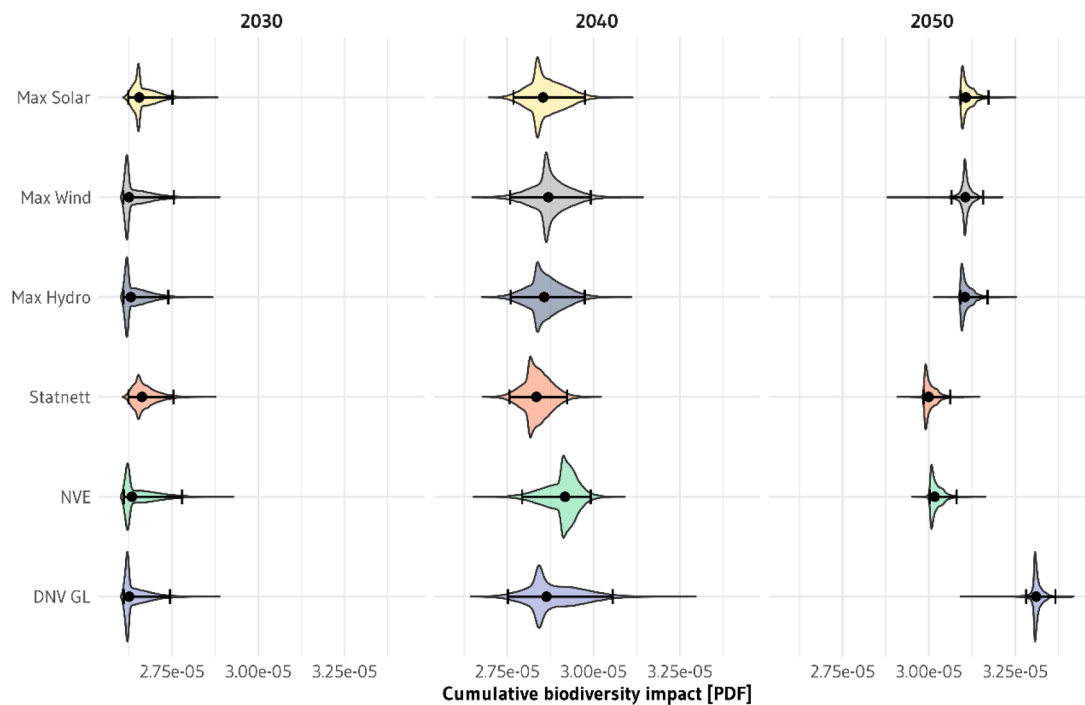


Fig. 8. The cumulative biodiversity impact from land pressure (PDF) due to increased electricity production across the six scenarios and three milestones. The top three scenarios are the technology-based scenarios (solar, onshore wind, and hydropower), while the bottom three scenarios are the report-based scenarios (Statnett, NVE, and DNV).

The technology-based scenarios show a steady increase in biodiversity impacts across all milestones, with no substantial differences between the technologies (see Table S10, Supporting Information 1).

From 2024 to 2050, the DNV, NVE and Statnett scenarios project an increase in biodiversity impacts of approximately 27.6, 16.4, and 15.7%, respectively. The technology-based scenarios indicate corresponding increases of 19.7, 19.9, 19.8% for maximised hydropower, wind, and solar power.

The width of the violin plots show how biodiversity impacts vary per scenario, depending on the selection of power plants across iterations. Thereby, suggesting that site selection towards projects with lower biodiversity impacts could mitigate some of the overall magnitude of the biodiversity effects of planned renewable energy projects. Nevertheless, the six scenarios indicate that the main driver of increased cumulative biodiversity impact is the projected amount of electricity production, as this will dictate the scale of renewable energy development in Norway. For instance, the DNV scenario expects Norway to produce 202 TWh of renewable energy on land by 2050 (DNV, 2024), an addition of about 50 TWh compared to the country's electricity production in 2024 (SSB, 2025).

If future electricity transmission primarily uses existing power lines rather than building new routes, biodiversity impacts would be substantially lower (see Figure S8, Supporting Information 2). This is consistent across all six scenarios.

4. Discussion

We conducted the first assessment of biodiversity impacts of operational and planned electricity facilities in Norway. We compared three renewable energy technologies: hydropower, onshore wind, and solar power. In addition, we calculated the biodiversity impacts of the current grid network and its potential future impacts based on projected electricity generation data. The indicators quantify the habitat loss impacts on species richness of four taxa: birds, herpetofauna, mammals, and vascular plants.

Our results suggest that the construction of hydropower, wind

power, and solar power negatively affects mostly birds and mammals, with the latter two technologies projected to increase their pressure on biodiversity due to further construction of renewable infrastructure. Studies about impacts related to land use change often show that the effects on amphibians are the highest (Dorber et al., 2020; Kuipers et al., 2021; Scherer et al., 2023). However, these studies focus on a global scale. The Norwegian amphibian taxonomic group, which also includes reptiles, consists of a lower number of species compared to the other taxa. Several species of this taxonomic group are concentrated in the southeast of Norway, while most of the planned power plants are located along the west coast. Furthermore, in Norway, birds belong to the taxonomic group with the most endangered species, followed by mammals and vascular plants (Artsdatabanken, 2021c).

Our findings show that spatial location and electricity production capacity affect the variation in the magnitude of their impacts on biodiversity. Site selection of energy facilities plays a key role in determining impacts on biodiversity (Estellés-Domingo and López-López, 2024; Gasparatos et al., 2017; Richardson et al., 2017). For instance, Grimsrud et al. (2024) showed that the potential spatial distribution for future onshore wind farms in Norway is greatly limited if biodiversity conservation is prioritised, while May et al. (2021) showed that the siting of operational onshore wind farms was driven mainly by economic aspects (i.e., the levelized cost of energy) rather than ecological (i.e., PDF). Prioritising power plant sites with relatively low biodiversity impacts, yet high production capacity, can contribute to achieving climate goals while minimising the overall impact on biodiversity. Our results indicate that most of the impacts originate from existing electricity infrastructure, with planned projects contributing only a small degree to the overall habitat loss. Yet even a small additional reduction in habitat size can lead to a greater loss of species richness, because in the SAR model the slope of the species-area relationship becomes steeper in smaller habitats.

Nevertheless, the projected amount of electricity in the future will dictate the increase in biodiversity impacts. Future projections, which cover the anticipated electrification across Norwegian sectors, assume that Norway's ability to meet its domestic needs and maintain its export

capacity may be greatly reduced by 2030 (Statnett, 2025). The expected reduced energy balance emphasises the urgency in planning and developing new renewable energy projects to achieve the climate goals of the European electricity market and the Norwegian climate plan, as indicated in a recent official Norwegian report (NOU 2023:3, 2023).

4.1. Renewable energy technologies in Norway

Across the technologies, hydropower had the highest effect on biodiversity. In Norway, existing reservoirs inundated more than 2000 km² (Harby and Carolli, 2022). Additional related habitat loss originates from dams, construction roads, power stations, pipelines or waterways, landfill sites, and power lines (KLD, 2024). The total extent of the Norwegian hydropower schemes is an obvious explanation for its current high effect on species richness. Norway has nearly 1,800 operational hydropower plants (NVE, 2024e), and more than 1,400 lakes serve as reservoirs (NVE, 2024d), contributing 89% of the domestic Norwegian electricity production (SSB, 2025). Although hydropower has the largest number of planned projects (i.e., more than 1,000), their cumulative potential habitat loss impact would remain smaller than the future expansion of onshore wind farms. As most of the potential for hydropower in Norway is already realised (NVE, 2020), future production focuses on upgrading and expanding existing power plants or developing small-scale projects (NOU 2023:3, 2023). Furthermore, since the infrastructure footprint of hydropower plants in Norway remains small (Kenawi et al., 2023, 2025), and future reservoirs will most likely be realised in existing lakes, we can expect a relatively small terrestrial habitat loss impact from future hydropower.

The most intensive development of hydropower plants in Norway occurred between 1960 and 1970, raising public concern regarding nature conservation. In response, the Norwegian government introduced the Norwegian Watercourse Protection Plan, protecting 390 watercourses from hydropower construction (ED, 2024; NVE, 2023b). Nowadays, some Norwegian politicians argue that new large-scale hydropower projects should be built in protected watersheds (Vartdal and Westhrin, 2024), which could generate an additional 49.5 TWh (NVE, 2020). Although the Norwegian government agreed that watershed protection should remain (ED, 2016), the development of small-scale projects in protected areas has been permitted since 2005 (ED, 2016; NVE, 2023b). Yet the development of projects with a capacity of over 1 MW in protected watersheds is allowed as a flood mitigation measure (Stortinget, 2025). In 70% of the Norwegian watersheds, hydropower plants already contribute greatly to negative effects on the aquatic environment (Alfredsen et al., 2022; KLD, 2024).

Our results suggest that planned onshore wind farms would cause the greatest effect on species richness due to habitat loss by 2050. Direct impacts of onshore wind power infrastructure may be limited to 1.6 km² per TWh (NVE, 2023a). Yet a larger area may be affected indirectly, as a planning area is estimated to be about 35 km² per TWh (NVE, 2022). While Norway has great potential to produce electricity from wind due to favourable wind resources (NVE, 2019b) and cost-effective conditions (NVE, 2024a), recent years have shown a dramatic decrease in public acceptance towards onshore wind turbines (Aasen et al., 2022). The local opposition to wind farms stems from various groups, ranging from environmentalists worrying about natural habitats, local governments arguing for equal economic benefits, and indigenous people protecting grazing lands for reindeer herds (Vasstrøm and Lysgård, 2024). The public resistance to onshore wind farms introduces uncertainty for its future development in Norway (NVE, 2025; Statnett, 2025).

As an alternative, the Norwegian government has promoted offshore wind as a prominent green industry (NFD, 2023), aiming to produce 26–87 TWh by 2050 (DNV, 2024; Statnett, 2025). Offshore wind enjoys a higher social acceptance in Norway compared to onshore (Aasen et al., 2022; Linnerud et al., 2022; Nytte et al., 2024). We did not address the potential impacts of future offshore wind farms, as our focus remains on land areas. This underestimates the future effects of renewable energy

on Norwegian species richness, as a wide-scale offshore wind development in Norway would affect marine biodiversity by disturbing marine species (i.e., by noise), affecting movement behaviour, changing species abundance and composition, and causing death by collision with turbines or vessels (Galparsoro et al., 2022; Watson et al., 2025).

While solar power contributes approximately 1% to Norway's electricity mix today (SSB, 2024b), it is expected to increase from 0.25 TWh (SSB, 2024b) to about 15–19 TWh by 2050 (DNV, 2024; Statnett, 2025). A ground-mounted solar power plant requires about 13–15 km² to produce one TWh (KLD, 2024). Our findings indicate that the future impact of solar power plants on species richness would be the smallest compared to onshore wind and hydropower plants. This could be explained by the relatively small number of planned solar projects. Nevertheless, solar power plants are the least efficient in terms of the relative biodiversity impact per GWh produced. Technological developments (e.g., higher efficiency in solar panels) or alternative set-ups (e.g., using hydropower reservoirs to deploy floating solar panels) may reduce the currently calculated, land-based biodiversity impacts. However, alternative set-ups may also lead to additional impacts on e.g., aquatic biodiversity that are currently unaccounted for and are outside the scope of this study. We recommend to update the results when large technological breakthroughs are foreseeable to guide the future energy landscape.

Norway has a massive annual electricity production potential for rooftop-installed solar panels (30–65 TWh) (Gholami, 2024; Myhre et al., 2025). Solar panel installation on buildings can greatly reduce the impacts of habitat loss, as energy facilities would be built on existing infrastructure (Gasparatos et al., 2017). Most of the potential lies in southeast Norway (Gholami, 2024; Myhre et al., 2025), a region known for high electricity consumption yet low current production capacity (Statnett, 2023). However, regulations and a lack of financial subsidies are major obstacles to the development of solar panels on rooftops in Norway. Furthermore, as electricity production by onshore wind power and hydropower is much cheaper and abundant (particularly the latter), investment in solar power remains less attractive (Xue et al., 2021). In our analysis, we accounted only for ground-mounted projects. Yet the development of ground-mounted plants in the coming years may remain limited due to grid capacity and land-use conflicts. Additional electricity production from solar energy will largely originate from roof-mounted installations (NVE, 2024c). Therefore, our results for biodiversity impacts by solar power may be somewhat overestimated.

4.2. Species accumulation curves

Gilad et al. (2024a) quantified the biodiversity impacts of the current operational Norwegian electricity system, assessing the effects of hydropower plants, onshore wind, and power lines. Similarly to our findings, their results indicate that hydropower plants and power lines pose the highest habitat loss impact on biodiversity compared to onshore wind. Nevertheless, their results suggest a higher overall habitat loss impact than our findings. This occurs due to different modelling approaches: Gilad et al. (2024a) estimated habitat loss impacts using a classic SAR for energy facilities and a species-habitat relationship (SHR) for power lines. Our study used a c-SAR (i.e., countryside) approach, applying the same model for each technology, ensuring a comparable methodology across all technologies. Classic SAR models assume that when natural habitats are converted into human-modified landscapes (i.e., from semi-natural habitat into highly modified habitat), biodiversity cannot persist in the altered environment (Martins and Pereira, 2017). This assumption overlooks the fact that species can survive in human-made landscapes and may lead to an overestimation, which can contribute to higher biodiversity impacts. We addressed this issue by adapting the c-SAR, accounting for species persistence in modified habitats. The SHR evaluates how habitat size and connectivity affect species richness (Kuipers et al., 2021; Scherer et al., 2023). Compared to SHR, c-SAR often results in lower biodiversity impacts, especially in the

case of strongly fragmented landscapes (Kuipers et al., 2021). This suggests a potential underestimation in our results, as our models only account for the relative habitat loss of power line corridors, yet do not address the indirect impacts of habitat loss (i.e., fragmentation). Additionally, our biodiversity impacts were multiplied by the GEP (i.e., global extinction probability), which result in much smaller PDF values compared to regional impacts (Kuipers et al., 2021).

4.3. Limitations and uncertainties

Our work focuses only on quantifying habitat loss, unlike Gilad et al. (2024a), who assessed additional impact pathways: barrier, collision, disturbance, electrocution, and water consumption. Nevertheless, across all the impact pathways, habitat loss accounted for about 62% of the total impact. This is particularly true for onshore wind, power lines, and solar power. Hydropower, however, also has an extensive effect on aquatic species and ecosystems, which we do not account for. Electricity production by hydropower affects water flow both upstream and downstream, leading to high stranding risk, reducing habitat suitability and fish population reproduction, and overall, decreasing species richness (Bozeman et al., 2024). Furthermore, run-of-the-river hydropower infrastructure causes river fragmentation, altering fish community composition and affecting species movement, particularly for migratory species (Geist, 2021; Gracey and Veronesi, 2016).

The accessible data on planned power plants in Norway allowed us to quantify the potential impacts of renewable energy on biodiversity while taking into consideration which habitats and taxonomic groups may be affected. Nevertheless, a large uncertainty remains about which power plants will be built. To achieve the expected electricity generation projections outlined in the scenarios, we used a random selection of planned power plants. This resulted in repeated sampling whenever the available data were insufficient to meet the scenario targets. The re-sampling approach may, however, underestimate the overall impact, as it relies on sites that undergone a licensing process. Yet as consumption demand is expected to continue growing, and as new power plants are likely to be built in areas with low land-use conflicts, new future sites may still be proposed in locations where economic or production interests outweigh biodiversity concerns. We incorporated all available planned projects provided by NVE, including unapproved projects unlikely to be built, to ensure a high variation of sampling subset of planned power plants. Incorporating unapproved projects was especially relevant for the DNV scenario, which predicts the highest increase in electricity production and the greatest biodiversity impacts.

Additionally, there is a strong variability across the technologies regarding area use. This is especially true for reservoirs and hydropower plants (see Supporting Information 2, Figure S4). We used empirical data to calculate habitat loss impacts, when possible, but a large degree of uncertainty remains regarding the actual infrastructure area of each power plant. Data gap was reported as a major limitation in other studies that aimed to quantify land use due to renewable sources in Norway (Dorber et al., 2018; Kenawi et al., 2023). As these studies were based on available satellite data, and since some remotely sensed data do not exist (i.e., before project development) or cannot be analysed (i.e., frozen lakes cannot be identified as water bodies, as mentioned by Dorber et al. 2018), this limitation is unavoidable.

Data availability also constrained the quantification of the potential impacts of power lines on biodiversity. Unlike power plants, there are sporadic data for future power lines available by NVE, potentially because the development process of power lines is known to be long (Lunde et al., 2022; NOU 2022:6, 2022; NOU 2023:3, 2023). In our analysis, we assumed that any additional generation capacity would require a proportional expansion of grid infrastructure. Nevertheless, as this study shows, the spatial location of energy infrastructure plays an important role in the magnitude of impacts. Therefore, the absence of spatial modelling for future power lines, which was excluded due to lack of data, resulted in limited findings on the impacts of future power line

expansion on biodiversity. Moreover, the existing data of operational power plants, reservoirs, and power lines, provided by NVE, may be incomplete and, therefore, introduce further uncertainty into our models.

Furthermore, the species occurrence data used in this study are based on habitat affiliation. Since we rely on the important habitats as defined by Artsdatabanken, the Norwegian national knowledge bank for biodiversity, this can introduce some inherent uncertainties. Moreover, our approach does not account for variation in habitat use or the relative importance of different habitat types, which may lead to an over-estimation of impacts for more common habitat types simply because they cover larger areas. In addition, our methodology does not incorporate habitat quality.

Finally, it is important to acknowledge that all human activities, including renewable energy deployment, cause biodiversity impacts. We should not forget the bigger picture. Transport, food production and construction are among the most impactful sectors. However, our focus in this paper is limited to the impacts of the Norwegian electricity generation, which mostly consists of renewable energy carriers already today.

5. Conclusions

In this study, we showed that the expansion of renewable energy in Norway on land is most likely to induce further habitat loss and increase pressure on biodiversity, particularly affecting birds and mammals. Additional pressure on marine species can be expected in the coming decades, if Norway achieves its goal: the installation of offshore wind farms with a capacity of 30 GW (NFD, 2023, 2025; NOU 2023:3, 2023).

The main driver of increased biodiversity impacts is the amount of electricity we will produce in the future, as this will determine the scale of renewable energy development. The three report-based scenarios from DNV, NVE and Statnett suggested a potential increase between approximately 16% and 28% in the cumulative biodiversity impact, corresponding to production goals of about 202, 185, and 184 TWh, respectively, from land-based renewable sources by the middle of this century. This was further reinforced by the technology-based scenarios, which apply identical production milestones (i.e., TWh) but distribute them differently across hydropower, onshore wind, and solar power technologies. The limited variation among scenario outcomes underscores that total electricity production, rather than the specific technology mix, is the dominant driver of projected increases in biodiversity impacts.

Prioritisation of “best-case” projects, i.e., power plants with low habitat loss impacts (i.e., PDF/GWh), has the potential to minimise the effects on species richness. Therefore, the development of power plants should avoid species-rich habitats. For instance, forests (i.e., where about 75% of the total area for planned solar power projects is located) or semi-natural habitats (i.e., which accounts for about 18% of the area for planned onshore wind farms). Projects should also be confined to already constructed or degraded areas. For example, the installation of solar panels on buildings minimises biodiversity impacts while access to the electrical grid is close by.

Energy efficiency measures can gradually halt the increasing electricity consumption rate and benefit biodiversity conservation, as they could reduce the building of new energy facilities. For example, measures within the building sector could reduce electricity consumption by 13 TWh and 40 TWh by 2030 and 2050 (respectively) (Sandberg et al., 2023). The Norwegian government recently published its action plan for energy efficiency (ED, 2023), aiming to reduce energy intensity and promote energy efficiency across the Norwegian economy. While there is a large potential for improving energy efficiency in Norway, its economic benefit may remain relatively small (NOU 2023:3, 2023). Furthermore, the decision-making process of implementing essential measures might not be fast enough, as it would involve multiple actors, such as industry stakeholders or housing associations (NOU 2023:3,

2023).

The outcome of this study is not only relevant to Norway. An energy transition is essential to mitigate the potential consequences of climate change, with its effects becoming more pressing. Climate change affects all countries and leads to a rapid change towards a global clean energy transition (IEA, 2024). Yet the expansion of renewables will contribute to additional land and sea use change, which is currently one of the main drivers of species extinction risk and reduction in species abundance (IPBES, 2019). As human society is greatly dependent on nature and its ecosystem functionality and services, the preservation of natural areas must be better prioritised through policies and planning strategies on regional, national, and global scales.

CRedit authorship contribution statement

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

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.cles.2026.100238](https://doi.org/10.1016/j.cles.2026.100238).

Data availability

Third-party data can be obtained directly from the original data providers as referenced in the methods. R-codes for conducting the analyses are available on GitHub (<https://github.com/jannebor/GridSAR>).

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