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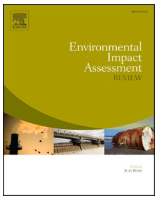

A spatially explicit environmental performance indicator accounting for different life-cycle impact pathways of onshore wind energy infrastructure

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A B S T R A C T

Environmental impact assessments (EIAs) are commonly used to identify negative effects of onshore wind farm projects on biodiversity and ecosystem services, but in practice they are often hampered by the lack of locally validated data. This reduces the robustness of decision-making, undermines stakeholder trust, and exacerbate local resistance. Methodological inconsistencies between EIAs and strategic environmental assessments (SEAs) further hinder the integration of environmental considerations across scales. In this study, existing life cycle assessment (LCA)–based biodiversity impact methods are extended to spatially quantify both direct and indirect effects of onshore wind energy on ecosystem services. The presented environmental performance indicator (NEP) for wind energy developments allows the consistent integration of impacts on ecosystem services and biodiversity. This connects site-specific project impacts to regional-scale assessments within the wider landscape. Using a wind farm project as a case study, the innovative NEP reveals spatially explicit impacts on recreational values through land occupation and disturbance. For impacts on avian diversity, waterfowl was the most vulnerable taxa due to disturbance and barrier effects. Regionalized impact mapping indicated that the planned wind farm had comparatively low avian impacts and moderate ecosystem service impacts relative to alternative sites. Comparison with the existing project EIA showed that the proposed LCA-based approach is consistent and provides a more extensive quantification of biodiversity and ecosystem service impacts. In addition, regionalizing impacts leads to impact benchmarks for comparing projects within the same region, supporting developers in early-phase scoping and improving decision-making to balance trade-offs between environmental impacts and economic revenues.

1. Introduction

Renewable energies are considered as an important technology to reduce greenhouse gas (GHG) emissions and simultaneously diversify the energy production to meet an increasing global energy demand. Onshore wind energy is among the fastest growing renewable energies and expected to reach a globally installed capacity of 570 GW within the next five years (*Renewables 2022 Analysis and Forecast to* 2027, 2026). However, while providing economic benefits and reductions in GHG emissions, wind energy infrastructure alters ecosystems and changes landscape into so-called energy landscapes (Pasqualetti and Stremke, 2018). Ideally, an optimal energy landscape produces renewable energy minimizing GHG emissions without causing detrimental impacts to landscape qualities and nature values (Pasqualetti and Stremke, 2018). However, several studies have shown that the construction and operation of wind turbines affect nature values, particularly through impacts on biodiversity (May et al., 2020; Ponitka and Boettner, 2020) and ecosystem services (Hastik et al., 2015; Martínez-Martínez et al., 2023). The impact of wind energy on biodiversity is mainly associated with biodiversity decline due to habitat alteration, disturbance and barrier effects for different species (Kati et al., 2021; Laranjeiro et al., 2018). Ecosystem services (ES) represent the direct (e.g. food from wild plants and animals, timber) and indirect (water retention, pollination) tangible as well as intangible (e.g. recreation, natural and cultural heritage) benefits nature provides to human well-being and societal welfare (Haines-Young and Potschin, 2010; Vasconcellos, 2023). Studies have demonstrated direct, in-situ impacts of wind energy on various ES, including water purification, water flow retention, and carbon sequestration (Picchi et al., 2019; Seifert et al., 2025). Additionally, research highlights more distant, indirect effects of wind energy on cultural ES, such as aesthetic and recreational values (Picchi et al., 2019).

To estimate the environmental consequences of wind energy

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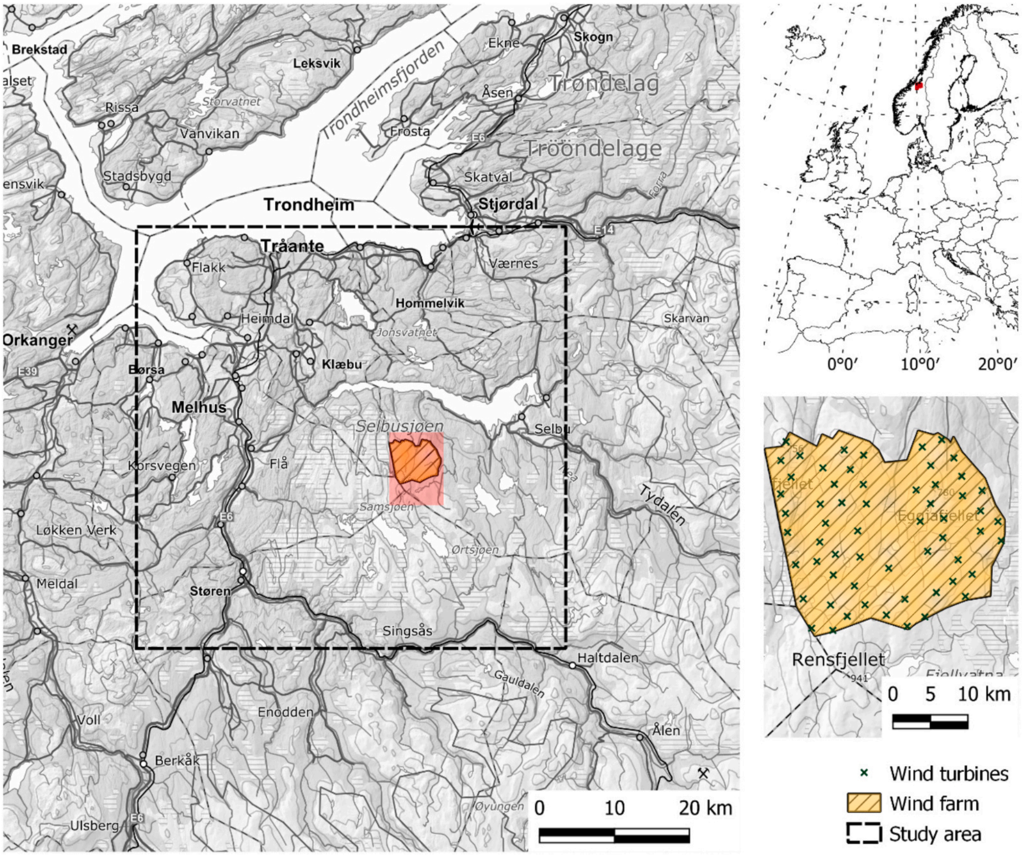

Fig. 1. Study area (dashed rectangle) and, planned Eggjafjellet wind farm project (yellow) and detailed turbine locations.

production, strategic environmental impact assessment (SEA) and project-level environmental impact assessment (EIA) are commonly applied. SEA is used to guide and coordinate wind energy development at regional or national scale as part of landscape planning processes (Dalal-Clayton and Scott-Brown, 2024). These planning-based approaches help to identify suitable sites for wind energy production through balancing socio-economic and environmental values (Hanssen et al., 2018; Josimović et al., 2021). Further, SEA can unravel potential trade-off or synergies between wind energy production and different landscape values and thus inform policy design and decision making (Egli et al., 2017; Hanssen et al., 2018; Salak et al., 2024; Spielhofer et al., 2023). In contrast, EIA incorporates project-specific parameters and locally relevant environmental data to assess, avoid, and mitigate the project's environmental impacts (Josimović et al., 2021; Kørnøv et al., 2025). Generally, EIAs involve lower data uncertainty than SEAs and specify potential wind farm locations within the boundary conditions defined by the SEA (Josimović et al., 2021).

Environmental impact assessments estimate and documents potential impacts of a wind energy project on biodiversity, particularly through habitat loss, disturbance and collision-related mortality (Perrow, 2017; Schuster et al., 2015). Besides estimating the biodiversity impacts, EIAs also analyse effects on landscape and associated natural and cultural values (e.g., aesthetics, recreational or cultural values) to identify mitigation options and potentially reduce social resistance. However, the use of EIAs) as a decision-support tools for wind energy project licensing has been criticized for shortcomings in quality and consistency, as well as for procedural, substantive, and transactive deficiencies (Chan et al., 2016; McMaster et al., 2021; Gulbrandsen et al., 2021; Inderberg et al., 2019; Smart et al., 2014; Larsen et al., 2018; Loomis and Dziedzic, 2018). Similarly, SEA practice has seen shortcomings in quality, early uptake to influence decision-making and tiering with EIAs (Dutta et al., 2021; Kørnøv et al., 2025), as well as appropriately assessing alternatives and cumulative effects (Geißler et al., 2021).

There exists still a need for more globally applicable predictive models that overcome these challenges to enhance the quality and consistency of SEA and EIA. Integrating spatially explicit, locally validated maps of environmentally sensitive areas has been proposed to enhance the effectiveness of EIA processes (Park et al., 2025). In addition, (Hoffman, 2017; Larrey-Lassalle et al., 2017) advocate for incorporating a life cycle perspective into impact assessments to better account for cumulative environmental effects and augment environmental justice. Life cycle assessment (LCA)—a widely applied methodology for quantifying the potential environmental impacts of goods, technologies, and services across their entire life cycle (Verones et al., 2017)—facilitates consistent comparison among policy, planning, and project alternatives and provides insight into cumulative impacts across regions and over time. Although LCA is constrained by limited availability and quality of site-specific data, insufficient data transparency, and incomplete uncertainty estimates ~~(Olanrewaju et al., 2024~~; ~~Satta et al., 2024)~~ integrating an LCA perspective into EIA can complement site-level assessments by offering a more holistic and globally informed view of environmental impacts (Hoffman, 2017; Larrey-Lassalle et al., 2017). Combining LCA and EIA have been proposed through the consideration of different life cycle phases (Iranmanesh et al., 2025; Larrey-Lassalle et al., 2017) or along different impact pathways (Laranjeiro et al., 2018; Loiseau et al., 2012). A complete EIA in conjunction with an LCA has been developed by (May et al., 2021) building on a spatially explicit life cycle impact assessment (LCIA) that quantifies the impacts of onshore wind energy on avian species. In this approach, impacts are assessed along multiple pathways such as habitat loss, disturbance, collision, and barrier, using locally validated species distribution models. In the LCIA biodiversity impacts are expressed as the relative loss of species richness using the potentially disappeared fraction (PDF) of species. The PDF therefore represents a spatially explicit measure of biodiversity impacts across different LCA impact pathways, applicable at both project scale and national scale, and offers the potential to closely integrate EIA and SEA (May et al., 2020; May et al., 2021). However, the PDF as a measure of impacts on biodiversity has not yet been integrated into EIA. In addition, the inclusion of wind energy impacts on ecosystem services into the LCA-EIA framework is still in its infancy (De Luca Peña et al., 2022; Othoniel et al., 2016). This study therefore has two main objectives. First, it aims to develop a spatially explicit, LCIA-based method for estimating impacts from direct and indirect (i.e. disturbance-related) area loss due to wind energy development on multiple ecosystem services. The method will be grounded in participatory, locally validated ecosystem service assessments, thereby demonstrating how site-specific data can be incorporated into LCIA. Analogous to the existing PDF for biodiversity, the method will derive a PDF for ecosystem services to enable integration of both into a holistic environmental impact metric. Second, using a planned wind farm in Norway, the study seeks to demonstrate how spatially explicit, LCA-based environmental impact quantifications can be integrated into project-specific EIA and subsequently applied to SEA.

2. Material and methods

2.1. Study area

The study area is located on the central Norwegian coast (63.4°N, 10.4°E) and covers 2782 km^2 in a region naturally conducive to the installation of wind turbines due to relatively high and constant wind speeds ($\mu = 6.75\ \text{m s}^{-1}$, $\sigma = 0.9\ \text{m s}^{-1}$) (Byrkjedal and Åkervik, 2009). The area includes the municipality of Trondheim and partly the municipalities of Selbu, Melhus, Skaun and Malvik (Fig. 1). Trondheim, with around 215,000 inhabitants, is the largest city in the study area and the district capital of Trøndelag County. The coastal lowlands and the Gaula Valley south of Trondheim are dominated by agriculture, settlements, and industry and have a “cold, no dry season, warm summer” (Dfb) climate (Beck et al., 2023). The south-eastern part of the study area is hilly, sparsely populated, and largely forested, with a “cold, no dry season, cold summer” (Dfc) climate (Beck et al., 2023). The “Eggjafjellet/Åsfjellet” wind farm project is located in the centre of the study area in hilly, predominantly open terrain and covers an area of 29 km^2. For this wind farm the concession process was paused in 2019 when a temporary moratorium on further development of onshore wind farms in Norway was imposed (Kaltenborn et al., 2023). Since the Norwegian government re-opened for applications for developing onshore wind farms in 2022, the “Eggjafjellet/Åsfjellet” wind farm is in the hearing phase. Currently no other projects are installed or planned within the study area. According to estimates by the Norwegian Water Resources and Energy Directorate (NVE) (Byrkjedal and Åkervik, 2009), the average annual wind speed at the wind farm site is $8.85\ \text{m s}^{-1}$ ($\sigma = 0.12\ \text{m s}^{-1}$) at 120 m above ground, placing the project site in the upper quartile relative to the study area. Given the favourable wind conditions, the project proposes the installation of 60 wind turbines with a hub height of 90 m, resulting in a total installed capacity of 200 MW and an estimated annual energy production of 613 GWh yr^{-1}. However, the project specific EIA (Mortensen et al., 2013) that has been conducted in 2017, emphasizes potential conflicts of the wind farm with biodiversity and ecosystem services. The area is known to inhabit several different vulnerable species including raptors, owls, gallinaceous birds and large carnivores (Mortensen et al., 2013). In addition, the EIA highlights potential impacts on recreational activities since the area is frequently used for hiking and skiing.

Given the availability of detailed operational parameters and the documented environmental concerns, the Eggjafjellet/Åsfjellet project provides a suitable case to demonstrate the proposed method and compare its outcomes with those derived from conventional EIA.

2.2. Mapping biodiversity

In this study, the biodiversity is represented by avian diversity, quantified as bird species richness. To allow the estimation of different impacts for different groups of species, functional groups of terrestrial birds were created based on taxonomy and functional similarities. The functional groups were corvids, gallinaceous birds, gulls, herbivorous songbirds, insectivorous songbirds, non-passerines, owls, polyphagous songbirds, raptors, waders, waterbirds and waterfowl (Appendix A. Supplementary data 1).

For each functional group, species richness maps were estimated by aggregating species distribution maps for common birds in Norway. MaxEnt software (version 3.4.3) (Philips et al., 2017), was used to run species distribution models (SDMs) and estimate occurrence rate for each species given data on occurrence and a set of ecologically relevant environmental variables. Occurrence data for birds were obtained from the Global Biodiversity Information Facility (GBIF, gbif.org) for the period 2000 to 2022 (Appendix A. Supplementary data 2). The data was limited to the Norwegian mainland and observations with an uncertainty larger than 0.5 km were excluded. Species occurrence data often exhibits a strong geographic bias, introduced by variation in accessibility and interest of observers between areas (Kadmon et al., 2004). Therefore, two methods were applied to minimise and handle the bias. First, by constructing a 1 km^2 grid, a systematic sampling of one record of each species per grid cell was conducted (Fourcade et al., 2014). After the systematic sampling, species with less than 50 records were excluded from the data. This removed species which are not commonly breeding, wintering or migrating in the area, and resulted in a total to 247 species had sufficient data available to estimate species distribution maps. Second, a “target-group” background was used while running SDMs, which replicates the spatial bias in occurrence records for the background samples. These methods have been shown to outperform other alternative methods for bias correction in SDMs (Barber et al., 2022; Fourcade et al., 2014). The target-group background was created by estimating a 2D kernel density using the occurrence records of all species and sampling background points from this density map (Barber et al., 2022). The SDMs were run with 10,000 background samples (without replacement), default regularization and were fitted allowing linear, quadratic, product and hinge features. Environmental variables used in the SDMs were annual mean temperature (°C), temperature seasonality (standard deviation × 100), annual precipitation (mm) and precipitation seasonality (coefficient of variation) downloaded from World climate variables (worldclim.org (Fick and Hijmans, 2017)), as well as global land cover 2019 (Buchhorn et al., 2020), elevation (GEBCO Bathymetric Compilation Group, 2023) and distance to the sea. To get the mean species presence probability, the Maxent raw output (species occurrence intensity) was transformed to occurrence probability using the complementary log-log (cloglog) transformation (Philips et al., 2017). Finally, the overall species richness for each functional group was estimated by summing the predicted species distribution maps (Grenié et al., 2020). The resulting maps for each functional group k show $S_kP_{k,i}$ for each grid cell i, where S_k is the number of species and $P_{k,i}$ [0 and 1] is proportional to the mean probability of presence (Philips et al., 2017). Species richness at each grid cell measured in this way then includes the suitability of the habitat through the probability of occurrence (Appendix A. Supplementary data 1).

Connectivity maps were estimated by applying circuit theory to the species richness map for each functional group using Omniscape (Landau et al., 2021; McRae et al., 2016) (version 0.5.8). Omnidirectional connectivity was estimated between every pair of locations

Table 1
Ecosystem services mapped using local stakeholders.

Ecosystem service	Description	CICES group
Existence value of Biodiversity	Existence value of biodiversity / ecosystems	Cultural
Recreation	Outdoor recreation and other recreation for physical and mental health	Cultural
Education	Nature as a source for science education and knowledge gain	Cultural
Place identity	Place identity (including natural and cultural heritage, landscape features, traditions)	Cultural
Spiritual experiences	Spiritual enrichment (e.g. contact with nature, sense of coherence, tranquillity and reflection, aesthetics)	Cultural
Wild plants	Wild plants, algae, fungi and their products people can benefit from	Provision
Wild animals	Wild animals and their products people can benefit from	Provision
Framing products	Agriculture/forestry products for nutrition, energy or other uses	Provision
Water quality	Regulation and maintenance of water quality	Regulation
Pollination	Pollination and seed dispersal	Regulation
Habitat quality	Maintain functioning populations and habitats	Regulation
Erosion control	Erosion prevention	Regulation
Climate regulation	Local climate regulation	Regulation
Pest control	Pest control	Regulation

within a circle with a radius of 50 km. The inverse species richness maps were used as resistance-to-movement rasters and the source of strength of each grid cell was set to the summed probability of presence $S_kP_{k,i}$. The resulting cumulative current flow map for each functional group from Omniscale were normalized (0,1) and multiplied by the number of species in the functional group to obtain a connectivity map with values $S_kC_{k,i}$. (Appendix A. Supplementary data).

2.3. Mapping ecosystem services

The spatial distribution of ES within the study area was assessed using a participatory matrix approach. In this approach the capacity of different land-cover types to provide ES are evaluated through experts (Burkhard et al., 2009). Based on the common international classification of ecosystem services (CICES V.5.1) (Haines-Young and Potschin, 2017), 14 ES across three ES groups were identified as relevant for the study area (Table 1). Land cover information for 15 classes was obtained from the Norwegian land cover raster (*Arealressurskart,* AR50) (Arealressurskart - AR50 Serie, 2026) with a spatial resolution of 50 m.

A total of 13 participants rated the capacity of all land-cover types to deliver ecosystem services using the ecosystem services matrix (Appendix A. Supplementary data 2). All participants were familiar with the ecosystem service concept and had professional backgrounds in environmental consultancy, municipal planning, or ecology. Capacity ratings were based on a five-point Likert scale ranging from 1 (“no ES potential”) to 5 (“high ES potential”) (Appendix A. Supplementary data 3). The individual ratings for each ES–land-cover combination were used to generate maps of ES capacity per participant, which were subsequently averaged across participants to derive mean ES capacity maps (Appendix A. Supplementary data 1).

For each ecosystem service k, the level of invariability was calculated to quantify the spatio-temporal consistency of ES distribution (Wang et al., 2017). In this context, invariability reflects the ES reliability across scales, where a higher invariability indicates more stable ES capacity at a given location and lower sensitivity to changes in the socio-ecological system (Wang et al., 2017). First, the squared coefficient of variation of ES k was calculated at the grid cell level using the individual ES capacity maps (Eq. (1)). Invariability (I) for ES k at grid cell i was then derived as the inverse of the squared coefficient of variation (Eq. (2)). Consequently, high I_k values represent relatively high mean ecosystem service capacity and low variation thus more stable ES capacity, whereas low I_k values indicate greater dispersion in ES capacity.

$$CV_{k,i}^2 = \frac{\sigma_{k,i}^2}{\mu_{k,i}^2} \tag{1}$$

$$I_{k,i} = \frac{1}{CV_{k,i}^2} \tag{2}$$

2.4. Quantifying the potentially disappeared fraction

The quantification of the impacts of a wind farm on avian diversity and on ES capacity was based on the generic concepts of the species-area relationship (SAR) (Storch et al., 2012) and the invariability-area relationship (IAR) (Wang et al., 2017), respectively. These relationships predict the effect of area loss on species richness or on the stability of ES capacity and is expressed in units of *potentially disappeared fraction* (PDF). In this study, PDF was used to quantify the potential loss of avian diversity (PDF_{Bio}) and ES capacity (PDF_{ES}) for the wind farm project. Both PDFs represent an impact measure of a wind farm f at a given location i and an impact pathway X, relative to all other locations in the defined study area. For PDF_{Bio} the relevant impact pathways are habitat loss, collision, disturbance and barrier to movement for birds (May et al., 2021). For PDF_{ES}, the identified pathways are land occupation and disturbance.

The equations for the calculation of PDF_{Bio} and PDF_{ES} for wind farm f and impact pathway X, at a given site (grid cell) i for a functional species group or ES k are defined in Eq. (3) and Eq. (4).

$$PDF_{Bio,X,k,f,i} = \frac{S_kP_{k,i}\left(1 - \left(\frac{A_{org,i} - A_{lost,X,k,f,i}}{A_{org,i}}\right)^{z}\right)}{\sum_{i=1}^{n} S_kP_k} \tag{3}$$

and

$$PDF_{Es,X,k,f,i} = \frac{I_{k,i}\left(1 - \left(\frac{A_{org,i} - A_{lost,X,k,f,i}}{A_{org,i}}\right)^{z_k}\right)}{\sum_{i=1}^{n} I_k}. \tag{4}$$

For both equations $A_{org,i}$ denotes the original area available at site i (here defined as one grid cell of 1 × 1 km) and $A_{lost,X,k,f,i}$ represents the area lost through impact pathway X for functional species group or ES k due to the construction of wind farm f. This part of the equations reflects on the area proportion remaining after to the construction of a wind farm, which is then translated into units of species richness or invariability by raising it to the power of z. The PDFs are thereafter calculated as the loss of species richness $S_kP_{k,i}$ or invariability $I_{k,i}$ for functional species group or ES k at grid cell i, relative to the total species richness or invariability summed across the entire study area. The exponent z for $PDF_{Bio,X,k,f,i}$ in Eq. (3) was set at the continental-scale SAR slope for birds in Eurasia of 0.21 (95% CI = [0.19, 0.22] (Storch et al., 2012);). In Eq. (4) the exponent z_k for $PDF_{Es,X,k,f,i}$ is defined as the slope of the log-log relationship between invariability and area within the study area (Hodapp et al., 2023; Wang et al., 2017). Because no globally valid z values exist for the IAR, the following procedure was applied to determine z_k for each ES k. First, I_0 was calculated for a randomly selected focal cell (A_0) within the study using Eq. (2). Subsequently, the area around A_0 was then iteratively expanded, with each new area I_{n+1} defined by squaring the side length of the previous area. A_{n+1} is then derived from the invariability of the smaller area (I_n) and the average correlation $\overline{p}_A$. $\overline{p}_A$ is the correlation of individual ES ratings averaged across grid cells in A_{n+1} (Eq. (4)) (Wang et al., 2017)). Using 40 randomly selected focal cells to calculate I_0, the mean and 95% CI were derived for each ES k (Appendix A. Supplementary data 1). Finally, the mean slope $\overline{z}_k$ was determined and applied to Eq. (4). Although the method introduces uncertainty related to the selection of I_0, a sensitivity analysis (Appendix A. Supplementary data 1) showed that variation in

I_0had no significant effect on the resulting z values.

$$I_{n+1} = I_n * \frac{A_{n+1}}{(A_{n+1}-1)*\overline{p}_A + 1} \tag{5}$$

A wind farm can have a footprint which might extend over several grid cells, thus the PDFs for wind farm f is the sum across all affected grid cells i, with $PDF_{v,X,k,f} = \sum_i PDF_{v,X,k,f,i}$, where $v = (Bio, ES)$. For avian diversity, the cumulative PDFs across impact pathways X or functional species groups k are estimated as $PDF_{Bio,X,f} = \sum_k PDF_{Bio,X,k,f} \sum_i S_k P_{k,i} / \sum_k \sum_i S_k P_{k,i}$ and $PDF_{Bio,k,f} = \sum_X PDF_{Bio,X,k,f} \sum_i S_k P_{k,i} / \sum_k \sum_i S_k P_{k,i}$. Hence, these cumulative PDFs area scaled to the sum of total species richness across functional groups. For the barrier impact pathway, the $S_k P_{k,i}$ in the above expressions and in Eq. (3). is replaced by $S_k C_{k,i}$. For ES, the cumulative PDFs for the impact pathways X are estimated as $PDF_{ES,X,f} = \sum_k PDF_{ES,X,k,f}$. The cumulative PDFs for each ES k are given as the mean PDF across impact pathways $PDF_{ES,k,f} = \frac{\sum_x PDF_{ES,X,k,f}}{n_k}$, whereas n represents the number of impact pathways for ecosystem service k. The total PDFs of a wind farm f is then given by $PDF_{v,f} = \sum_X PDF_{v,X,f} = \sum_k PDF_{v,k,f}$.

2.4.1. *Area lost for different impact pathways*

The area lost due to the development of wind farm f depends on the impact pathway X. Wind farm f contains l_f turbines numbered $w = (1, \ldots, l_f)$. For impact pathway X in functional species group or ES k, the impacted area of each wind turbine can be defined as a circular buffer $F_{X,k,f,w}$ with centroid at its coordinates (x, y). These buffers can overlap if the impacted area is large relative to the distance between turbines. The total area impacted for wind farm f can then be given by the union of all wind turbine buffers $F_{X,k,f} = \bigcup_{w=1}^{l_f} F_{X,k,f,w}$. The area lost for grid cell i in a map through impact pathway X can now be given by $A_{lost,X,k,f,i} = a\left(F_{X,k,f} \bigcap R_i | F_{X,k,f} \bigcap R_i \neq \emptyset\right)$, where R_i is a polygon representation for grid cell i with area $A_{org,i.}$

Habitat loss (H) or land occupation (L)

Habitat loss or land occupation relates to the physical, direct alterations of land cover on the footprint of the fundaments, other infrastructure and maintenance areas of wind turbines. This is quantified both for avian diversity and ES by the area required for the foundation of a turbine and the surrounding infrastructure (a_{EP}), which increases with the capacity of the turbine in MW[62]. The permanently impacted area can be estimated by 0.003 km^2/MW (95% CI = [0.0026, 0.0033]) and the temporary impacted area estimated by 0.007 km^2/MW (95% CI = [0.0062, 0.0078]) (Denholm et al., 2009). The area lost for functional species group k due to habitat loss or land occupation for wind turbine w in wind farm f can then be given as $A_{lost,O,k,f,w} = a_{EP} EP_w$, where a_{EP} is the sum of permanently and temporary impacted area (0.01 km^2/MW, 95% CI = [0.0088, 0.0111]) and EP_w is the installed nominal capacity of wind turbine w.

Disturbance (D)

Disturbance relates to the alteration of the physical or acoustic landscape through artificial installation; and is quantified for avian diversity and for three cultural ES (recreation, place identity, spiritual experiences). For the other ES this impact pathway was not deemed relevant. The area lost for wind turbine w in wind farm f due to disturbance for avian diversity can be given by $A_{lost,D,k,f,w} = \pi d_k^2$, where d_k is the mean disturbance distance for functional species group k. 95% confidence intervals for the disturbance distance in each group were estimated by assuming a log-normal distribution with parameters μ and σ^2. A parametric bootstrap was performed with sample size equal to the number of species in the given group with data on disturbance distances as measured by flight initiation distances (FID) obtained from the literature (references are provided in the dataset provided in the Appendix A. Supplementary data 2. When multiple estimates were available from different sources the maximum FID was used. Given the sample mean d_k and variance $\sigma_{d_k}^2$, the parameters of the log-normal distribution is given by $\mu = \ln\left(d_k^2 / \sqrt{d_k^2 + \sigma_{d_k}^2}\right)$ and $\sigma^2 = ln\left(1 + \sigma_{d_k}^2 / d_k^2\right)$. Then, 1000 bootstrap replicates of d_k were simulated and 95% confidence intervals calculated as the 2.5% and 97.5% percentiles of the bootstrap distribution.

The area lost for wind turbine w in wind farm f due to disturbance for ES k was given by $A_{lost,D,k,f,w} = \pi\left(D_k d_{k,max}\right)^2$ (adopted from May et al., 2020). The disturbance factor (D) follows

$$D_k = \int_{d=0}^{d_{k,max}} \frac{1 - 1 \Big/ 1 + e^{\beta\left(d - d_{k,max}\right)}}{d_{k,max}} d\partial \text{ (May et al., 2020), where } \beta = \frac{\log((2-\alpha)/\alpha)}{d_{k,min} - \overline{d}_k} \text{ with } \alpha = 0.1$$

The disturbance distances d were derived from the distribution of the invariability of ecosystem services I, defined as those areas with $I_k > Q_{95}(I_k)$, and thus specific for the study area and ES k. The Euclidean distances for all grid cells i in the study area to the nearest hotspot grid cell were calculated. From the cumulative distribution function (CDF$_k$) across the study area, $d_{k,max}$ equals 80% of the CDF for the distances. For $d_{k,min}$ 0 has been chosen and $\overline{d}_k$ as the 50% of the CDF (Appendix A. Supplementary data 1).

Collision (C)

Birds in the rotor swept zone around each turbine are at risk of colliding with the rotating blades. (Thaxter et al., 1862) have estimated species-specific collision rates (c) with 95% credible intervals. The area lost due to collision is estimated as the rotor-swept area multiplied with the probability of collision (May et al., 2020). The probability of at least one collision per year is estimated as $p_k = 1 - e^{-c_k}$ (), where c_k is the mean collision rate for functional species group k from (Rathi, 2022). The area lost for wind turbine w in wind farm f due to collision can then be given as $A_{lost,C,k,f,w} = p_k \pi r_{f,w}^2$ (Beck et al., 2023), where $r_{f,w}$ is the rotor radius (measured in km).

Barrier (B)

Barrier effects relate to the fragmentation of habitats due to land occupation and disturbance from wind turbines which potentially influences movement expenditure of birds in the wider landscape. This barrier effect is proportional to the area lost due to disturbance $A_{lost,D,k,f,w}$. For wind turbine w in wind farm f, the area lost due to barrier effects can be given by $A_{lost,B,k,f,w} = M_k A_{lost,D,k,f,w}$ (), where M_k is the mean total energy requirement for migration which can be estimated by $M_k = 2 a_k l_k$, where a_k is the energetic requirement per km travelled and l_k is the distance travelled per season averaged for the species in functional species group k (Somveille et al., 2018). found that the energetic requirement per km for a bird species can be given by $a = 6.07 \times 10^{-5} m^{-0.01}$, where m is the mean body mass of the species (in kg). Body masses for all species were obtained from (Tobias et al., 2022) and migration distances from (Vincze et al., 2018).

2.5. *Regional PDFs*

PDFs are relative measures of impact depending on the extent of the region under consideration. Regional-scaled impacts tend to be higher, as species may become locally extinct more rapidly than they do at the global scale (May et al., 2021; Kuipers et al., 2019). To directly compare PDF$_{Bio}$ and PDF$_{ES}$ and to evaluate how a planned wind farm performs in terms of avian diversity loss or ES loss within the region, the PDF values of the wind farm can be contrasted with PDFs calculated for alternative locations across a broader study area. This was achieved using a moving-window approach based on the wind-farm footprint. The footprint was iteratively centred on each grid cell in the study area, and the PDFs were recalculated and assigned to the respective cells. This procedure produced spatial maps representing the PDF values for all possible siting alternatives. The resulting PDFs were subsequently normalized

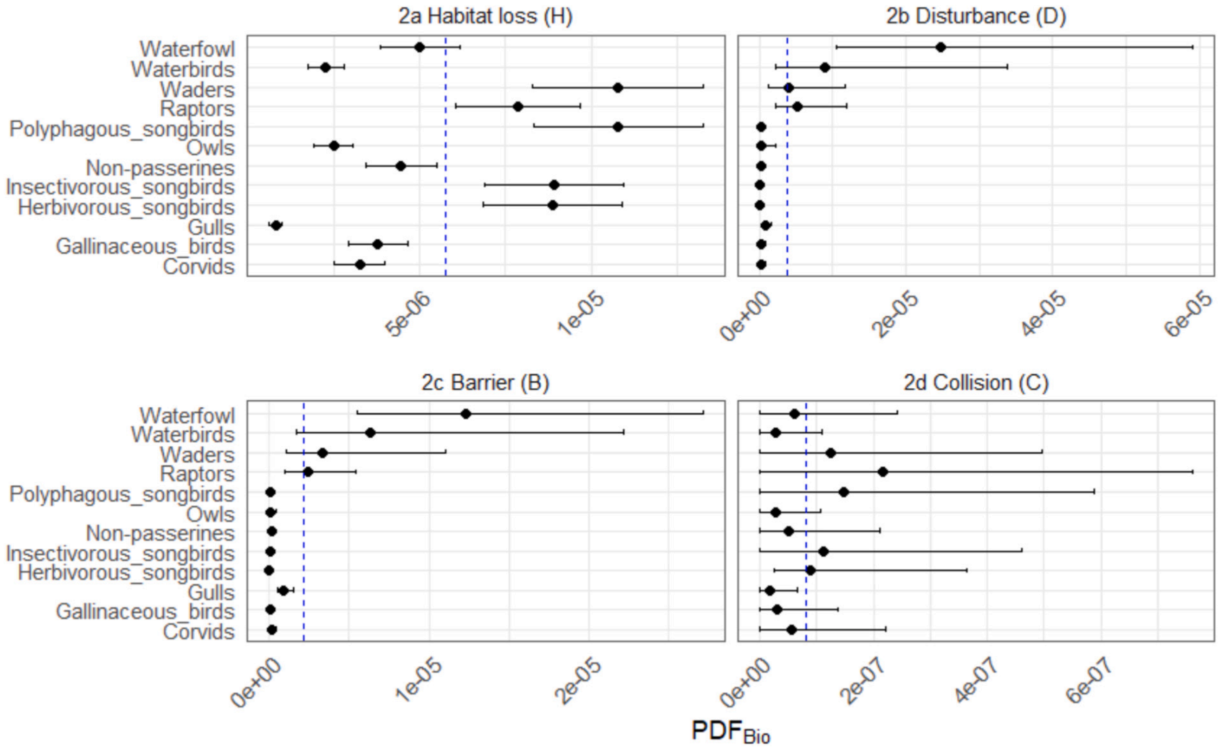

Fig. 2. Potentially disappeared fraction (PDF) of functional species groups in the proposed wind farm area for different impact pathways. Error bars indicate 95% CIs. Dashed line shows the average PDF_{Bio} per LCA impact pathway.

(PDF^*_{Bio}, PDF^*_{ES} ϵ [0,1]) using a linear min-max transformation.

Based on the regional PDF*, the net environmental performance (NEP) indicator represents a holistic measure of performance for the combined impacts on avian biodiversity and ES. It indicates the impact of a wind farm in relation to the theoretical impact of the same wind farm placed at any other location within the study area and thus sets the impact in relation to the wider landscape. By using the normalized PDF*s, the NEP for wind farm f follows $NEP_f = 1 - \left(PDF^*_{ES,f} + PDF^*_{Bio,f}\right)0.5$ assuming equal importance weights for biodiversity and ecosystem services. These weights can in principle also be adjusted when of interest.

To analyse potential trade-offs between economic viability and environmental impacts (NEP), levelized cost of energy (LCOE) estimates and maps for Norwegian onshore wind energy were adapted from NVE (Storch et al., 2012) (Appendix A. Supplementary data 1). According to NVE, the national LCOE for onshore wind energy in 2017 was estimated at 0.039 USD kWh^{-1}, whereas the proposed wind farm exhibits a lower estimated LCOE of 0.032 USD kWh^{-1}.

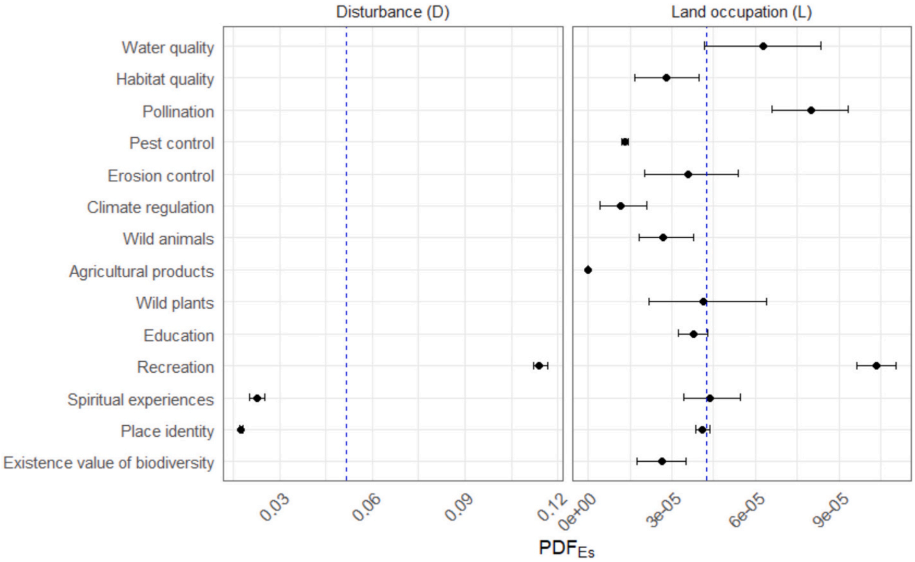

Fig. 3. Potentially disappeared fraction (PDF) of ecosystem services in the proposed wind farm area for different impact pathways. Error bars indicate 95% CI. Dashed line shows the average PDF_{ES} impact per LCA impact pathway.

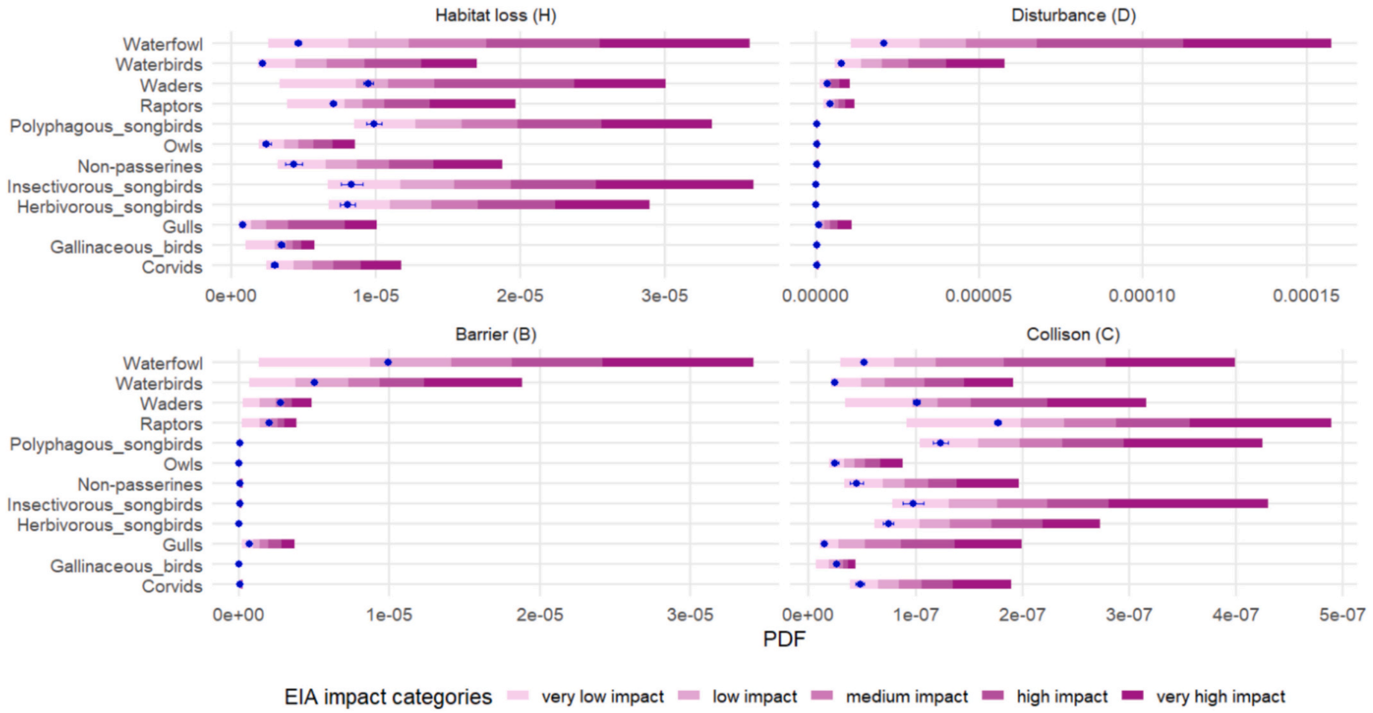

Fig. 4. Jenks classified impact (PDF_{Bio}) of the wind farm for all functional groups and all impact pathways compared to regional PDF^*_{Bio} of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To contextualize the magnitude of project-specific impacts (PDF) within the study area, the Jenks natural breaks clustering algorithm was applied to the regional PDF* values. Using a predefined number of classes, the algorithm minimizes within-class variance while maximizing differences between classes. The Jenks natural breaks method is widely used for visualizing spatial data with high variance. Given the pronounced spatial variability in the resulting PDF* values, impacts were classified into five categories: very low, low, moderate, high, and very high. Owing to its simplicity, the Jenks classification can be easily adapted to national or local guidelines for classifying impacts used in environmental impact assessments (EIAs). However, because Jenks class boundaries are determined by the data distribution rather than by external (e.g. policy-defined) thresholds, the resulting classes are only valid for the spatial extent of the PDF* dataset, i.e. the case study area.

3. Results

3.1. *Environmental impact assessment of the wind farm project*

Fig. 2 shows that within the area of the planned wind farm, the greatest impact on avian diversity (PDF_{Bio}) across all functional groups is caused by habitat loss (H), followed by disturbance (D), barrier effects (B), and collision risk (C). A Kruskal–Wallis test indicated significant differences of PDF_{Bio} among the four impact pathways across all species

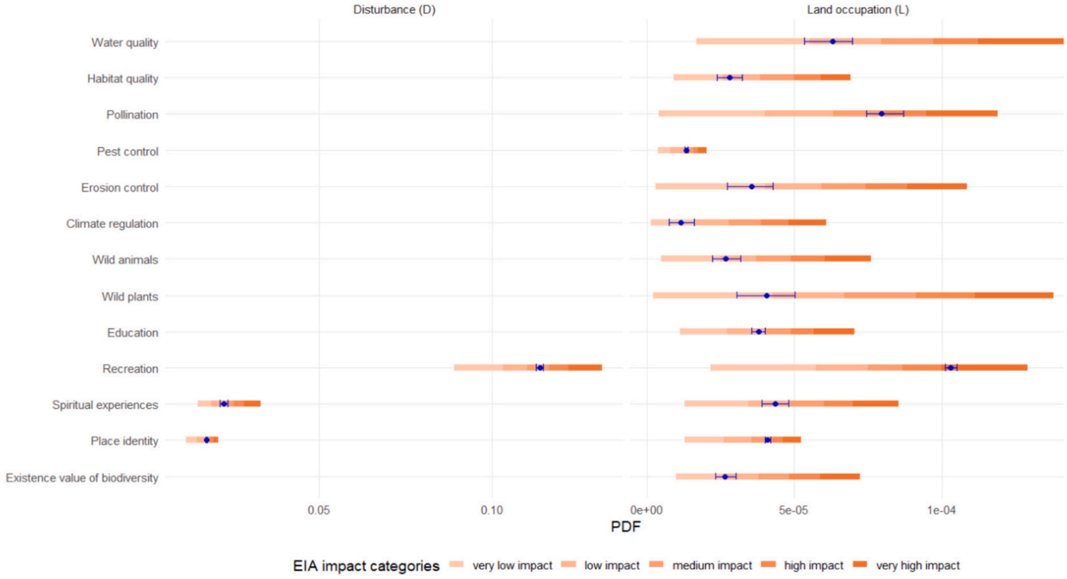

Fig. 5. Jenks classified impact (PDF_{ES}) of planned wind farm (blue) on ecosystem services and all impact pathways, compared to the regional PDF^*_{ES} of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

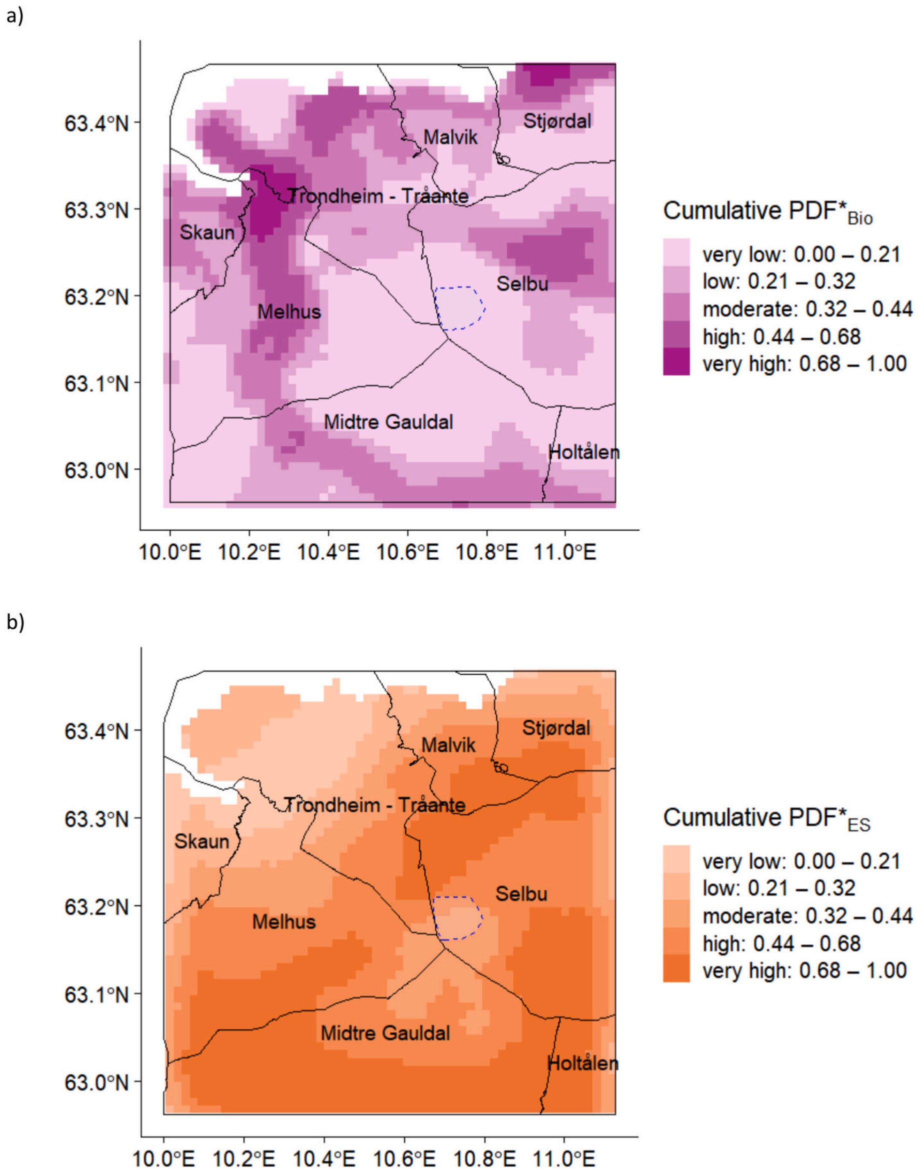

Fig. 6. Jenks classified cumulative PDF*$_{Bio}$ (6a) and PDF*$_{Es}$ (6b) for the whole study area. The planned wind farm area is indicated in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

functional groups ($X^2 = 22.9,\ p < 0.001$). Post-hoc pairwise Wilcoxon tests with Hochstrasser correction revealed that the impact of habitat loss was significantly greater than that of disturbance ($r = 0.44,\ p < 0.04$), barrier effects ($r = 0.54,\ p = 0.01$), and collision risk ($r = 0.84,\ p < 0.001$). No significant difference was detected between disturbance and barrier effects ($p = 0.2$). However, disturbance effects were significantly greater than collision risk ($r = 0.7,\ p < 0.001$). Finally, no significant difference was found between the two pathways with the smallest overall impact, barrier effects and collision risk ($p = 0.13$).

All functional groups are affected by habitat loss (Fig. 2a), with particularly high impacts observed for waders, raptors, and songbirds. Disturbance and barrier effects are most prominent for waterfowl, waterbirds, raptors, and gulls, whereas songbirds are generally less affected (Fig. 2b and c). Although collision risk represents the smallest overall impact, Fig. 2d shows that all functional groups are nevertheless exposed. Raptors, songbirds, and owls are specifically exposed to wind turbine collision within the wind farm. However, collision risk within the wind farm area seems to have noticeable uncertainty across all species functional groups (Appendix A. Supplementary data 1).

For the cultural ecosystem services (recreation, place identity and spiritual experiences), median disturbance impacts were approximately three orders of magnitude higher (D, $M(PDF_{ES}) = 0.05$) than those from land occupation (L, $M(PDF_{ES}) = 5{*}10^{-4}$) (Fig. 3). This difference reflects the broader spatial extent of disturbance effects, which reach up to 13 km from the wind farm. Recreational values were most affected, as areas with high recreational use overlap with the proposed wind farm location. A Kruskal test indicated no significant differences of PDF$_{ES}$ among the different ecosystem services within the impact pathway groups ($p(L) = 0.4,\ p(D) = 0.2$). Nevertheless, for land occupation the largest impacts were found for recreation, water purification, and pollination, whereas climate regulation was less affected because the planned wind farm area contains neither wetlands nor forests. No impact was detected for agricultural production, as the wind farm is located far from agricultural areas, which are primarily situated in the valleys (Appendix A. Supplementary data 1).

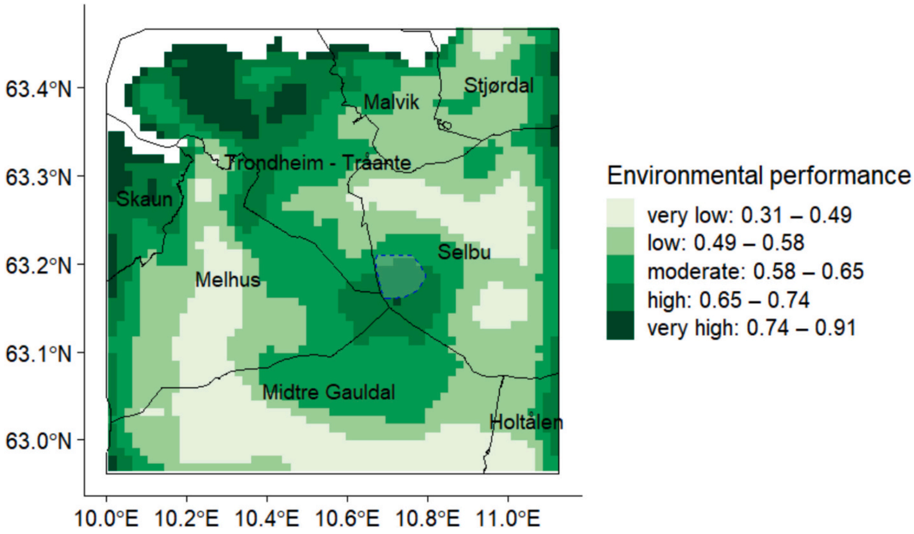

Fig. 7. Jenks classified net environmental performance map (NEP) based on combined impact on avian diversity and ecosystem services The planned wind farm area is indicated in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

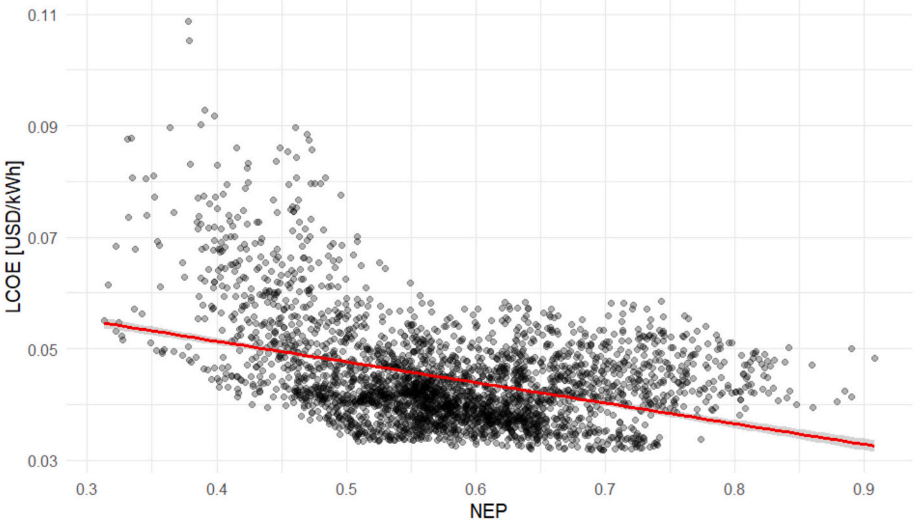

Fig. 8. Spearman's rank correlation between NEP and LCOE for case study area.

3.2. *Contextualized impact*

For avian diversity the impact classification reveals that none of the impacts for the wind farm area can be considered as *high* or *very high* (Fig. 4, Appendix A. Supplementary data 1). However, the planned wind farm is expected to have medium barrier effects on waders and gallinaceous birds, whereas for all other species functional groups and impact pathways low impact can be expected.

The wind farm project is likely to have *very high impact* on recreational and high impact on pollination ecosystem services due to land occupancy (Fig. 5, Appendix A. Supplementary data 1). Medium impacts can be expected due to disturbance effects on place identity, spiritual experiences and recreation. Thus, the planned wind farm area can be considered as high impact area particularly for cultural ecosystem services in comparison to the whole study area.

3.3. *Strategic environmental assessment of the study area*

For all functional bird groups and across all impact pathways, areas of high and very high impacts on avian diversity are primarily concentrated around Gaulosen, the Gaula River valley delta extending from south to northwest in Melhus municipality, near Lake Selbusjøen in central Selbu municipality, and along the coastal areas of Stjørdal municipality. In contrast, the planned wind farm is situated in a region characterized by generally low impacts on avian diversity. (Fig. 6a). Fig. 6b shows that high aggregated ES impacts are expected particularly from Stjørdal municipality toward the southern parts of Trondheim municipality, as well as in the southwestern portion of the study area. These areas are predominantly hilly and forested, are easily accessible, and are therefore frequently used for recreational activities.

3.3.1. *Combined net environmental performance (NEP)*

The NEP for the study area represents the inverse of the combined impacts on avian diversity and ecosystem services. Areas with high NEP (i.e., lower environmental impact) occur mainly along the coast, largely due to the high proportion of built-up areas. The planned wind farm area also exhibits high environmental performance, reflecting relatively low impacts on birds and only moderate impacts on most ecosystem services (Fig. 7).

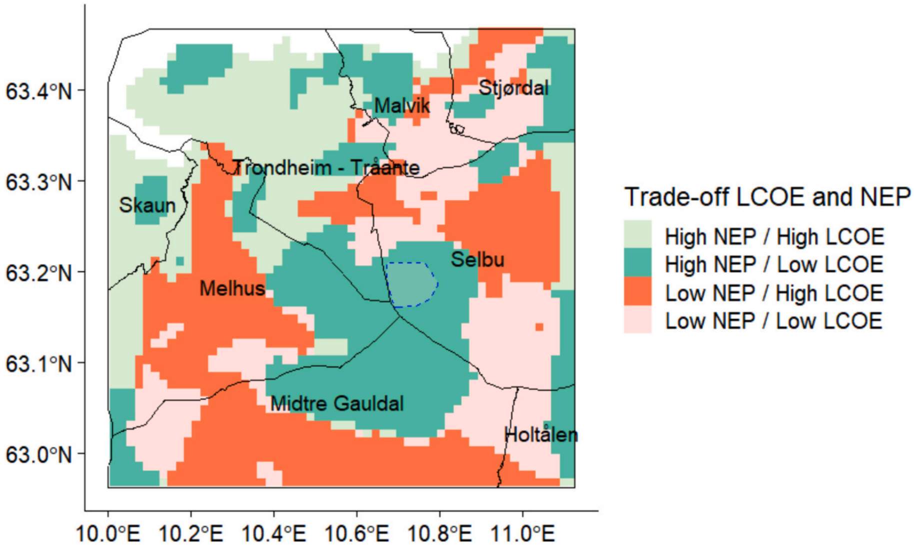

Fig. 9. Areas of trade-offs and synergy between environmental performance (NEP) and costs (LCOE).

3.3.2. Spatial synergies and trade-offs of environmental performance and energy production costs

Spearman's rank correlation was used to assess the relationship between NEP and LCOE. The analysis revealed a significant negative correlation ($\rho = -0.30$, $S = 5.86 \times 10^9$, $p < 0.001$) indicating that higher environmental performance tends to be associated with lower energy costs within the case study area (Fig. 8).

Fig. 9 illustrates the spatial classification of trade-off outcomes. Areas with high environmental performance (NEP > Q_{50}(NEP)) and low costs (LCOE < Q_{50}(LCOE)) are identified as favourable (dark green), whereas areas with low environmental performance (NEP < Q_{50}(NEP)) and high costs (LCOE > Q_{50}(LCOE)) are considered unfavourable (dark red). The remaining two classes represent trade-off areas, where either environmental performance or economic viability is favourable, but not both. Although the Eggjafjellet/Åsfjellet wind farm is located within a synergistic area characterized by high NEP and low LCOE, the resulting trade-off map also highlights additional potential sites that combine low costs with high environmental performance.

4. Discussion

This study introduces $PDF_{ES,}$ a novel and spatially explicit LCIA-based indicator for quantifying the impacts of onshore wind farms on ecosystem service (ES) capacity across two distinct impact pathways. By grounding the assessment in participatory mapping of ES capacities and their spatial invariability, the method incorporates site-specific and locally validated information. In parallel, the approach is aligned with established LCIA methods for estimating impacts on avian diversity (PDF_{Bio}) (May et al., 2020, 2021). By using a planned wind farm project in Norway as a case study, the applicability of both PDF_{ES} and PDF_{Bio} to spatially explicit project assessments is demonstrated, allowing detailed impact quantification across multiple pathways, ecosystem services, and functional species groups. The study also illustrates how the magnitude of project-level impacts can be contextualized through regionally extrapolated PDFs. The regional PDFs show hypothetical impacts across a broader region and can support the identification of alternative locations in EIA or inform strategic environmental assessment (SEA). Finally, both indicators are integrated into a combined measure of environmental performance (NEP), which is compared with levelized wind energy establishment costs (LCOE).

Project-specific impacts were found to be particularly high for recreational values, driven by both disturbance and land-occupation effects. When compared to the potential impacts at alternative locations within the broader study region, the impacts on recreation were classified as high. PDF_{Bio} indicated that barrier effects on waders and gallinaceous birds were of medium magnitude relative to other areas, whereas low impacts were estimated for all remaining species functional groups and impact pathways. The NEP analysis showed that the planned wind farm is situated in an area with above-average regional NEP, indicating relatively low combined environmental impacts within the context of the wider region. Moreover, a negative correlation between LCOE and NEP was identified, indicating that several valuable project alternatives might be available with low costs and high environmental performance provided detailed thematic information on the different causes of impact—namely land occupation, habitat alteration, disturbance, barrier effects, and collision risks—across multiple functional species groups and ecosystem services. Tables 2 and 3 present a comparison of the quantified PDFs and the impacts described in the EIA for the planned Eggjafjellet/Åsfjellet wind farm project (Mortensen et al., 2013).

The comparison demonstrates that the PDF_{Bio} provides more detailed and precise information on the species affected, as the metric is derived from species distribution models. Whereas the original EIA characterizes habitat-related impacts as minor relative to other impact categories, the spatially explicit analyses indicate that habitat alteration represents the strongest impact across all assessed bird species, exceeding both collision- and disturbance-related effects. The application of PDF_{Bio} within an EIA therefore enables a more holistic and detailed assessment of avifaunal impacts associated with a specific project.

Uncertainty in EIAs has frequently been communicated through qualitative wording (Larsen, 2021), however, the use of quantitative impact metrics in combination with field data would allow this uncertainty to be reduced and explicitly quantified. Furthermore, the a priori use of PDF-based analyses can assist in planning field surveys more efficiently, addressing a well-documented challenge in EIA practice (Karlson et al., 2014).

With respect to ecosystem services, the EIA of the Eggjafjellet/Åsfjellet wind farm project does not explicitly address impacts on provisioning or regulating services associated with land occupation. In contrast, the present study demonstrates that land occupation is likely to particularly affect regulating and cultural ecosystem services. Regarding disturbance effects, the project EIA notes visual impacts on landscape characteristics and emphasizes the wide visibility of the project area. These findings are supported by the results of this study, which indicate substantial disturbance-related impacts, especially on recreational values and landscape aesthetics. Impacts on landscape characteristics

Table 2
Potential specification of existing project EIA by the application of the PDF_{Bio} for avian diversity.

Impact pathway	Original EIA statement (Mortensen et al., 2013) (translated from Norwegian)	Proposed potential specification using PDF for avian diversity
Habitat alteration	*The size of the degraded area is limited and usually not a significant negative factor compared to the other points discussed. However, the direct loss of land can be significant if wind turbines, roads or other infrastructure are built in places with particularly valuable biotopes for birds (p.133)* *Direct land use as a result of the development will lead to reduced available habitat for many bird species. However, these areas are small compared to the available area in the planning area. Birds associated with water and wetlands will be negatively affected by drainage as a result of roads and other excavation.* (p.136)	Habitat alteration caused due to land cover change through the proposed wind farm project affects all bird species. Across all species, habitat alteration has the greatest impact values among all impact pathways. Most impact is expected on waders, raptors and various songbird species. Compared to the larger area surrounding the proposed wind farm, the habitat alteration impacts can be classified as minimal to medium.
Disturbance	*With increased human activity, birdlife will be disturbed to a greater extent than today, and this will have a particularly negative impact on some species during the breeding season. One example of such a species is the black-throated loon (near threatened), which is very sensitive to disturbance (p.137).*	For waterfowl, disturbance will be the most prominent effect in the wind farm area. Waterbirds, waders and raptors are less affected by disturbance
Barrier effects	*Migrating pink-footed geese fly over Selbu and Klæbu, passing the planned wind farm. Thus, the development of the area will create additional barriers across a corridor used by these migrating birds (p.161).*	Most impacts due to barrier effects can be expected for waterbirds and waterfowl. For waders and gallinaceous birds, the planned area can even be considered as medium impact area, compared to all other areas in the wider area surrounding the wind farm.
Collision risk	*Certain species, particularly larger birds of prey, are at greater risk to collide with the turbines* (p.135).	Among all impact pathways and across all functional groups, collision risk is the lowest impact. In the wind farm area, raptors and waders seem to have higher risk of collision than other functional groups. However, the analysis revealed highest uncertainty in the quantification of the collision risks and thus conclusions should be drawn based observation data.

and cultural values are commonly estimated in EIAs through geographic viewshed analyses and visualizations. By contrast, the PDF_{ES} applied in this study is based on ecosystem service capacity maps derived from participatory assessments. Consequently, the proposed indicator accounts for impacts on locally validated nature benefits to humans. The direct integration of stakeholder knowledge and values into a quantitative EIA assessment enhances communication of wind farm projects and ultimately has the potential to improve project acceptance (Larsen et al., 2018).

Beyond providing more detailed information on affected species, ecosystem services, and the underlying impact mechanisms—issues that have been highlighted as persistent challenges in EIA practice (Karlson et al., 2014) —the PDFs also have the potential to substantially enhance the interpretative quality of EIAs. In particular, the assessment of impact significance has been identified as a critical challenge for EIA practitioners (Jones and Morrison-Saunders, 2016; Ehrlich and Ross, 2015). Drawing on insights from psychological research, recent work has emphasized the need to (a) strengthen the evidentiary basis for significance judgements and (b) promote the use of statistical models to support such evaluations (Retief et al., 2023). The regional PDFs presented in this study contribute to both requirements by providing contextual information that enables project-specific PDFs to be compared with hypothetical impacts at alternative locations, thereby facilitating an estimation of impact magnitudes. In addition, this relative, spatially explicit measure of impact directly addresses common shortcomings in EIAs related to the contextualization and comparison of project alternatives within the broader landscape (Jiricka-Pürrer et al., 2018; Rathi, 2022). In line with (Iranmanesh et al., 2025) the study demonstrates that LCIA-based, project specific PDFs can complement EIA by supplying quantitative, systematic information of different impact pathways.

Conversely, the regionalized PDFs and NEP maps can be directly used to support SEA and regional planning by providing an integrated measure of environmental impact, thereby enhancing the effectiveness of environmental protection as emphasized by Kørnøv et al. (2025) and Perrow (2017). In addition to supporting the identification of environmentally sustainable areas, the regionalized PDFs can be used to locate areas with high potential for ecosystem restoration to mitigate impacts from onshore wind energy developments, as suggested by[11]. Moreover, both the regional PDFs and the NEP can be calculated for different project parameters (e.g., turbine size, number of turbines, wind-farm configurations) and across different impact pathways, thereby enabling scenario analyses, highlighted as an essential component of SEA (Kealey and Alderman, 2025).

The integration of economic and social dimensions together with the NEP into spatial multi-criteria decision analysis (Hanssen et al., 2018; Egli et al., 2017) or optimization frameworks (Spielhofer et al., 2023; Salak et al., 2024) can further facilitate the identification of optimal production sites, the development of regulatory plans, and the formulation of policy recommendations. Moreover, the combination of the NEP with for example the LCOE enables to unravel areas of trade off or synergies between different planning aspects. Such integration enables planners and policy makers to account for environmental impacts that extend beyond individual project boundaries and across administrative units. Although the approach was applied to a regional case study involving several municipalities, the PDFs could also be scaled to the national level. Taken together, the project-specific and regional PDFs offer substantial potential to strengthen the connection between EIA and SEA by providing a common and comparable measure of environmental impact. In the Norwegian context, this directly responds to the identified need for more integrated assessments of landscape values at the regional scale, including the consideration of cumulative impacts (OED, 2026).

Although the presented method and results contribute to improving both EIA and SEA and to bringing these procedures closer together, several limitations must be acknowledged. First, the PDF_{ES} was derived from ES capacity maps. This reflects the potential to provide ES (La Notte et al., 2019) but does not account for the actual supply or use of the ES. For impacts on cultural ecosystem services resulting from disturbance, the fraction of lost ES use may be more relevant for estimating public resistance or for justifying planning decisions.

Second, several parameters required for calculating the PDF_{ES} were estimated and influence the resulting values. The critical distance parameters were defined as the 0% and 80% quantiles of the cumulative distribution of minimal distances between ecosystem-service hotspot areas. Although this procedure accounts for the spatial distribution of nature values in the study area, the choice of these parameters affects the area considered lost through disturbance and should ideally be determined through stakeholder involvement or expert judgement. Deriving threshold values for impact distances from local questionnaires or photo-based surveys conducted as part of an EIA could further strengthen the local anchoring of the analysis. Another crucial

Table 3
Potential specification of existing project EIA by the application of the PDF for ecosystem services.

Impact pathway	Original EIA statement (Mortensen et al., 2013) (translated from Norwegian)	Proposed potential specification using the PDF for ecosystem services
Land occupation	Not explicitly mentioned	Despite agricultural values, all ecosystem services will be affected through land occupation of the wind farm. In comparison to other areas, the proposed wind farm has very high impacts on recreation, pollination.
Disturbance	*For landscape characteristics and cultural values, significant negative impacts can be expected (p.51-54 / 69)*	*The development of the proposed area will lead to significant and high disturbance impacts on cultural landscape values, such as place identity, spiritual experience and recreation potential.*
	Recreation *The wind farm is planned in areas that are not primarily used for outdoor recreation, nor are there any organized activities linked to the planning area. However, what is special about the area is that it is untouched and defined as wilderness. It therefore has a special value for user groups seeking unspoiled areas. The facility is located on a ridge and will therefore be visible from long distances. This means that wilderness areas outside the actual planning area will also be affected by the facility. The area's identity as Trondheim's wilderness will be lost (p.94).*	

parameter for the PDF calculation is z in the SAR and IAR which determines the magnitude of species richness or ecosystem services loss for a given reduction of the originally available area. The SAR describes one of the fundamental relationships observed in ecology, as the area increased so does the species richness (Schoener, 1976). For biodiversity, z must be statistically derived based on species occurrence data across different spatial scales, revealing the generality of the SAR but that z differs between taxa and may differ among continents (Storch et al., 2021). The relationship may further be affected by differences in local factors such as microclimate, habitats and environmental change, but as shown in island studies area is generally the primary factor explaining variation in species richness (Kalmar and Currie, 2006). Thus, continental scale SAR estimates of z should be useful in metrics for the general loss of species richness following area loss. In contract to biodiversity, the slope of the invariability–area relationship must be calculated separately for each study area and each ecosystem service (Appendix A. Supplementary data 1). Consequently, when the method is applied, a regionally valid sensitivity analysis of z is strongly recommended, and any associated uncertainty should be carefully propagated and transparently communicated within the resulting PDF values.

Third, the application of a moving-window approach to calculate regional PDFs may introduce edge effects and artefacts in the regional PDF maps. In the present study, a larger initial study area was selected, and the final PDF maps were subsequently cropped to the intended extent to remove such edge effects. Moreover, the moving-window technique inherently generalizes fine-scale spatial patterns of species occurrences or ecosystem service capacities. For analyses of urban expansion, moving-window studies have indicated an optimal resolution of approximately 1′800–2′200 m (Wang et al., 2021). In this study, the footprint of the wind farm determined the size of the moving window. Particularly when large wind-farm footprints are used relative to the initial mapping resolution, the resulting generalization effects require systematic examination.

Finally, while the PDF_{Bio} can be calculated for large areas, the PDF_{ES} relies on locally validated ecosystem service capacity maps. Consequently, reference areas for regional PDF assessments can only be extrapolated to a limited degree, as ecosystem service valuations may differ across landscape types. The choice of spatial scale therefore remains critical. In this study, an arbitrary area surrounding the project site was defined, and the wind farm's impact was evaluated relative to this reference area. Hence, the selected spatial scale directly influences the estimated impact level. In Norway, most planning decisions are made at the municipal level, which could therefore provide an appropriate reference scale for analysis. By contrast, conducting assessments at the national scale would likely require methodological adjustments to the calculation of the potentially lost fraction of ecosystem services.

5. Conclusions

The proposed LCA-based approach integrates multiple impact pathways on both biodiversity and ecosystem services into a single net environmental performance indicator for a given wind-farm project. By regionalizing these impact measures, EIA and SEA are brought closer together using common, spatially explicit impact quantifications. This strengthens communication between strategic and project-level planning and facilitates the early and effective consideration of natural values within wind-energy development processes.

It is therefore suggested that policy makers adopt PDF-based impact measures as a standardized component of EIA for predefined, environmentally relevant aspects (e.g., selected ecosystem services or key species). From a technical perspective, this requires that EIA consultancies incorporate species distribution models and ecosystem-service maps, ideally co-produced with local communities. However, the PDFs and the derived NEP should be treated as a first-stage screening tool to identify potentially suitable areas for wind-energy development. A second stage should involve local field surveys of biodiversity and ecosystem services within areas identified as having high NEP. Such a two-step procedure supports transformative change by reinforcing the “avoidance” step of the mitigation hierarchy (May, 2019), rather than relying predominantly on compensatory (Kørnøv et al., 2025). Transformative change is further supported through the inclusion of local stakeholders in mapping important nature-benefit areas, thereby improving project credibility and reducing impacts on highly valued ecosystem services.

Additional research is needed to further examine the assumptions underlying key parameters (e.g., z) used in the PDF_{ES} and PDF_{Bio} calculations, in order to better characterize the sensitivity of these parameters and their influence on the final impact quantifications. Furthermore, PDF metrics should be developed for additional life-cycle phases, as impact mechanisms and their spatial configurations may differ substantially from those considered in the operational phase. In collaboration with EIA practitioners, regional planners, and decision makers, future work should also examine the implications of generalizing project-specific PDFs to regional PDF, given the associated reduction in spatial resolution. Finally, effective approaches for communicating and visualizing PDF-related uncertainties require further exploration to support transparent and robust decision making.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT V4 to support the formulation of some text segments. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2026.108471.

Data availability

Data and code is available in this repository https://doi.org/10.17605/OSF.IO/BV97Q.

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Glossary

CDF: Cumulative distribution function
EIA: Environmental impact assessment
ES: Ecosystem services as direct and indirect benefits from ecosystems to human
GHG: Greenhouse gas
GW: Gigawatt (10^9 watts) measures the capacity of power plants
GWh yr^{-1}*:* Gigawatt-hours per year measure of electricity output
IAR: Invariability-area relationship
LCA: Life cycle assessment
LCIA: Life cycle impact assessment
LCOE: Levelized cost of energy
MW: Megawatt (10^6 watts) measure the capacity of power plants
NEP: Net environmental performance indicator as the combination of ecosystem service and biodiversity impact measure to be used at project or regional level.
PDF: Potential disappeared fraction, as a relative impact measure using different LCA impact pathways.
PDF_{Bio}: PDF calculated for impacts on mapped species richness
PDF_{ES}: PDF calculated for impacts on mapped ecosystem service benefits.
SAR: Species-area relationship
SEA: Strategic environmental impact assessment for landscape planning at different spatial scales
SDM: Species distribution models