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Development of a collision impact indicator to integrate in the life cycle assessment of offshore wind farms

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Abstract

Purpose Life cycle assessment (LCA) is a robust approach to estimate the environmental impacts of an offshore wind farm (OWF). However, methodological hurdles remain, particularly the lack of appropriate indicators to assess ecosystem impacts during OWF construction and operation and the scarcity of marine ecological data. To address the lack of indicators, this article focuses on developing an impact indicator specifically related to bird collision with OWFs.

Methods To assess bird collisions during the operation of OWFs, we adapted a life cycle impact indicator originally developed for onshore wind farms. This indicator combines spatial data on bird species distribution and vulnerability to collisions with OWF technical characteristics (number of turbines, power production, rotor diameter).

Results The results model and map seabird collisions at OWF worldwide and introduce a biodiversity impact characterization factor into LCA. The results are expressed as the potentially disappeared fraction of species (PDF) annually per gigawatt-hour (GWh) and vary between $2.0e^{-15}$ and $1.69e^{-13}$ PDF.year/GWh. It correlates 1344 bird species distribution with the locations of 226 operational and 181 planned OWFs. The spatial differentiation of the characterization factors highlights the OWF collision impact variability worldwide. Such mapping is crucial for identifying areas with varying levels of risk, which is essential for the strategic planning of OWFs. Projections indicate higher potential collision risks in Asia than in Europe, and future expansion of the OWF into new regions with higher collision potential is expected to increase collision risks. In addition, the main factors affecting collision intensity were statistically identified. Therefore, to mitigate collisions, it is essential to focus on three key aspects: fewer turbines, smaller rotors, and greater distance from the shoreline. In addition, the LC-IMPACT method was employed to compare the collision impacts for two OWF projects in France, with those resulting from climate change. Over the lifetime of these OWFs, the collision impacts are quantified at around $2.0e^{-7}$ PDF, where effects attributed to climate change will be six times higher.

Conclusions The development of this collision indicator is a first step towards integrating OWF biodiversity impacts into the LCA framework. It also demonstrates how LCA indicators can inform marine spatial planning in the context of marine renewable energy development.

Keywords Environmental assessment · Biodiversity indicator · Potentially disappeared fraction of species (PDF) · Characterization factor (CF) · Spatialized impacts · Bird Collision

1 Introduction

Life cycle assessment (LCA) is currently one of the most widely used methods for characterizing the environmental impacts linked to all life cycle stages of a system or product (Hauschild and Huijbregts 2015). LCA can provide a comprehensive framework for estimating the potential environmental and human health impacts of manufacture, use, and disposal of emerging technologies. In the context of renewable energy technologies, offshore wind farms

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Highlights
- Spatialized potential bird collision impact with offshore wind farms.
- The number of turbines or the turbine diameter significantly influences bird collisions.
- Currently, planned future offshore wind farms have not avoided sites with bird collision impacts.
- The LCIA-based tool is promising to account for trade-offs between electricity production and conservation.

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(OWFs) represent a promising solution (Pezy et al. 2020). As the world transitions away from fossil fuels due to climate change, the European Union alone anticipates a 25-fold increase in electricity production from offshore wind power between 2020 and 2050 (Commission Européenne 2020).

However, the development of offshore wind power, similar to onshore wind power, faces criticism due to its potential impact on ecosystems. OWFs can have both desirable and undesirable effects on biodiversity. For example, OWF structures generate hard substrates that serve as reefs, supporting sessile organisms, but simultaneously, they may disrupt sedimentary habitats or reduce functional habitats for fishes and birds (Degraer et al. 2020; Lindeboom et al. 2011). To fully assess these impacts, LCA can provide valuable insights.

Birds are among the taxa most widely affected by offshore wind energy through either attraction or aversion caused by the structures (Garthe and Hüppop 2004— Supplementary Information 1.1). Four impacts are hereby important: (1) collisions with wind turbine blades, (2) displacement in response to disturbances such as light and noise, (3) barrier effects impacting bird flight routes, and (4) loss of functional habitats (Bradbury et al. 2014). Among them, collision impact is expected to lead to the highest bird mortality (Garthe and Hüppop 2004; Petersen and Fox 2007) and is one of the most controversial and publicly discussed impacts of wind electricity production in general (May et al. 2021). Hence, OWF managers and decision-makers need spatially explicit and quantified information on potential collision impacts to identify the most at-risk marine areas. Regions with large numbers of OWFs and high-collision potential should therefore be identified. OWF decision-makers must consider the presence of migratory birds in these high-collision potential areas, sensitive species circulating within the OWF area, threatened species, and bird densities (Marques et al. 2014; May et al. 2020a). Such mapping is lacking at the global scale to inform the worldwide development of the wind energy sector (Laranjeiro et al. 2018).

Although the impact of the collision remains the best-known effect of OWF on birds from a qualitative point of view, only limited quantified information exists (Cook et al. 2018). Studies on avifauna are mainly based on observation data from ships, aircraft, and radar, which are expensive, time-consuming, and difficult to generalize. Consequently, most of the studies are based on models (Cook et al. 2018) and are based on a limited number of species as we can see in our literature review (Supplementary Information 1.2 1) . Only the study of Vanermen et al. (2013) and Everaert and Stienen (2007) quantified the collision impact based on in situ and radar observations in the Belgian OWFs for a small number of bird species known to be sensitive to collisions. Quantification of the collision impact in the marine environment is therefore based on 24 species only, the transferability of which to other studies remains to be proven, due to the variability of the impact relative to the context (Leemans and Collier 2022). The most comprehensive data on collision impacts are based on onshore wind farm studies, ranging from 0.3 to 18.3 birds killed per wind turbine per year (median 4.5, Gaultier et al. 2019).

Other studies have identified that the potential impact of bird collisions at onshore windfarms depends on the number of turbines and the geometrical parameters related to their size (e.g., height, diameter) (Thaxter et al. 2017). Similar findings are expected for OWFs. Today, OWFs have on average 44 turbines, with turbine diameters between 65 and 136 m and heights between 95 and 165 m. These numbers are expected to increase with the next OWF generations (Díaz and Guedes Soares 2020).

Anticipating the impact of technical and engineering changes on the OWF collision impact and, in particular, estimating the impact per unit of energy produced are both critical to a comprehensive environmental assessment and to reveal the efficiency and environmental trade-offs of various turbine designs and OWF layouts. A major strength of LCA is that it can assess multiple environmental impacts at the same time to identify trade-offs between them. The international standards ISO 14040 and 14044 (International Organization for Standardization 2006a, 2006b) consider four stages for LCA: after goal and scope definition and inventory analysis, the impact assessment step translates the different emissions and resource uses into quantified environmental impacts using so-called characterization factors (CFs), which are later discussed in the interpretation (Hauschild and Huijbregts 2015). The climate change impact of a product or system, for example, is estimated using CFs translating greenhouse gas emissions, such as CH_4, into CO_2 equivalents based either on radiative forcing or global temperature change potential (IPCC 2023). Despite recent efforts to include an increasing number of impacts in LCAs (May et al. 2020a, 2021), only a few studies consider the direct environmental impacts occurring during the operation phase of OWFs (Jingjing et al. 2023; Li et al. 2023), and none exists that estimates the impacts of OWF on birds due to collisions.

The objective of this study is therefore to develop spatially explicit CFs in order to include the potential impacts of OWF on birds due to collisions in LCA studies. The CFs are expressed as the potentially disappeared fraction of bird species due to collision with OWF in relation to the electricity produced by the OWF (PDF/GWh). These CFs can be used to evaluate the current and future OWF impacts on bird species' richness for different regions in the world.

This paper first describes the procedure to derive the CFs. Second, the CFs are used to estimate and spatialize bird collisions within each currently operational OWF and within each OWF planned or under construction across the globe. Third, a statistical analysis identified the parameters influencing the collision impacts the most. Finally, the collision impact is compared to the climate change impact for two French OWF projects, estimated with an LCA-specific impact assessment method, LC-IMPACT.

2 Materials and methods

2.1 Model overview

The collision indicator developed by May et al. (2020a, b) was used as a starting point and adapted to analyze the bird collision impacts on OWF. May et al. (2020a) developed a species distribution model (Laranjeiro et al. 2018) to quantify the impacts of onshore wind farms on birds, distinguishing between impacts due to habitat loss, disturbance, and collision. The proposed indicators express impacts in terms of a fraction of species potentially disappeared in response to these impacts, expressed as "potentially disappeared fraction of species" (PDF) in LCA.

We chose to only focus on collision, since modeling disturbance and habitat loss for marine bird species are difficult because (i) habitat preferences for seabirds at sea are almost non-existent and (ii) land-use models do not apply at sea.

May et al. (2020a) first developed a collision impact indicator for a set of bird orders expressed in PDF.year, considering the engineering characteristics of a wind farm (i.e., number of turbines, blade length) and a collision coefficient estimating the sensitivity of the species to collision (Fig. 1 A). Secondly, the CF for collision was derived by summing the collision impact of species across all bird orders potentially affected and dividing it by the annual electricity produced per OWF, expressed in GWh. This represents the functional unit typically used in LCA for electricity production systems (Fig. 1 B). The resulting CFs are expressed in PDF.year/GWh.

May et al. (2020a, b) calculated this CF for collisions at the global scale for each operational onshore wind farm ($n = 23{,}068$) and identified the most sensitive bird orders. They also proposed a regionalized CF for 110 countries, corresponding to the sum over the CF of the operational onshore wind farms in each country. In the remainder of this article, the CF by OWF is referred to as "CF_{OWF}" and the regionalized CF is referred to as "$CF_{regional}$."

2.1.1 Adaptation of the model to the offshore wind farm context

To apply a similar approach to OWFs across the world, some changes were made to the calculations as compared to May et al. (2020a, b). First, the mapping resolution was changed to the spatial hold of the OWF, which is much larger than wind farms on land. According to our global wind farm database, onshore wind farms have on average 10 turbines, while OWF has 44 turbines. Finally, a new $CF_{regional}$ was proposed based on marine ecoregions and exclusive economic zones rather than per country.

To go further and propose a new prospective application of the method, we also calculated the CF_{OWF} and $CF_{regional}$ for future OWF projects that were planned, accepted, or

Formulas used in May et al. 2020 for collision impact

A ***Collision impact formula (PDF.yr)***

$$PDF_{k,w} = \frac{S_k nP_{k,i} n \left(1 - \left(\frac{A_{org,i} - R_k nt_w n\left(\pi nr_w^2\right)}{A_{org,i}}\right)^z\right)}{\sum_i^I S_k nP_{k,i}}$$

B ***Characterization factor formula (PDF.yr/GWh)***

$$CF_w = \frac{\sum_{k=1}^{K} PDF_{k,w}}{E_w}$$

k = bird order w = wind-power plant i = site

$PDF_{k,w}$ = Collision impact PDF per year of the order k for a wind-power plant w
$S_k nP_{k,i}$ = Number of Species S of the order k, Potentially present locally at the cell i
A_{org} = Area size, that correspond to the resolution of the raster map used
R_k = Collision coefficient of the bird order
nt_w = One turbine of the wind-power plant
nr^2_w = Number of rotor blength length r of the turbine (squared to obtain the rotor diameter)
z = Slope of the species-area relationship on a logarithmic scale
CF_w = Characterization factor CF of the wind-power plant
E_w = Annual energy production E per wind-power plant (Ew in GWh)

Fig. 1 Equations for calculating the potentially disappeared fraction of species from May et al. (2020a, b) under construction at the time of this study (January 2021). To be able to analyze the potential evolution of collision impact, we then chose to map the CF_{OWF} and $CF_{regional}$ both for the current situation, considering only OWFs in operation, and for the future situation, considering future OWF projects.

The overall formulas developed by May et al. (2020a) were adopted, as well as the methodological approach using R-coding (version 4.2.1, packages: "sf," "rgdal," "raster," "sp," "XLConnect," "lme4," "lmerTest," "MuMIn," "FactoMineR," "Factoextra"), from which the previously cited changes in the calculations and the data were adopted.

2.1.2 Assessing the collision impact and mapping the characterization factors for offshore wind farms

The most important step of the methodology development consisted of assessing the collision impact for each bird order studied, using the PDF formula proposed by May et al. (2020a). This methodological section and Fig. 2 present an overview of the processes to develop the collision impact indicator and to derive from it the characterization factors CF_{OWF} and $CF_{regional}$. The specific methodological choices made in the data preparation are explained in the next methodological Sect. 2.2.

The collision impact was considered a product of the birds' vulnerability to collisions, the site's sensitivity, and the exposure to collision (adapted from Freduah et al. 2018). For each pixel occupied by an OWF, the relationship between these three variables was calculated: (i) the collision coefficient provided information on the birds' vulnerability to collisions, (ii) species richness indicated site sensitivity, and (iii) the exposure to collisions corresponded to the surface area covered by the sum of the rotors of the turbines of an OWF. Finally, the collision impact per order per offshore wind farm was obtained, expressed in PDF per order per farm (Fig. 2 B).

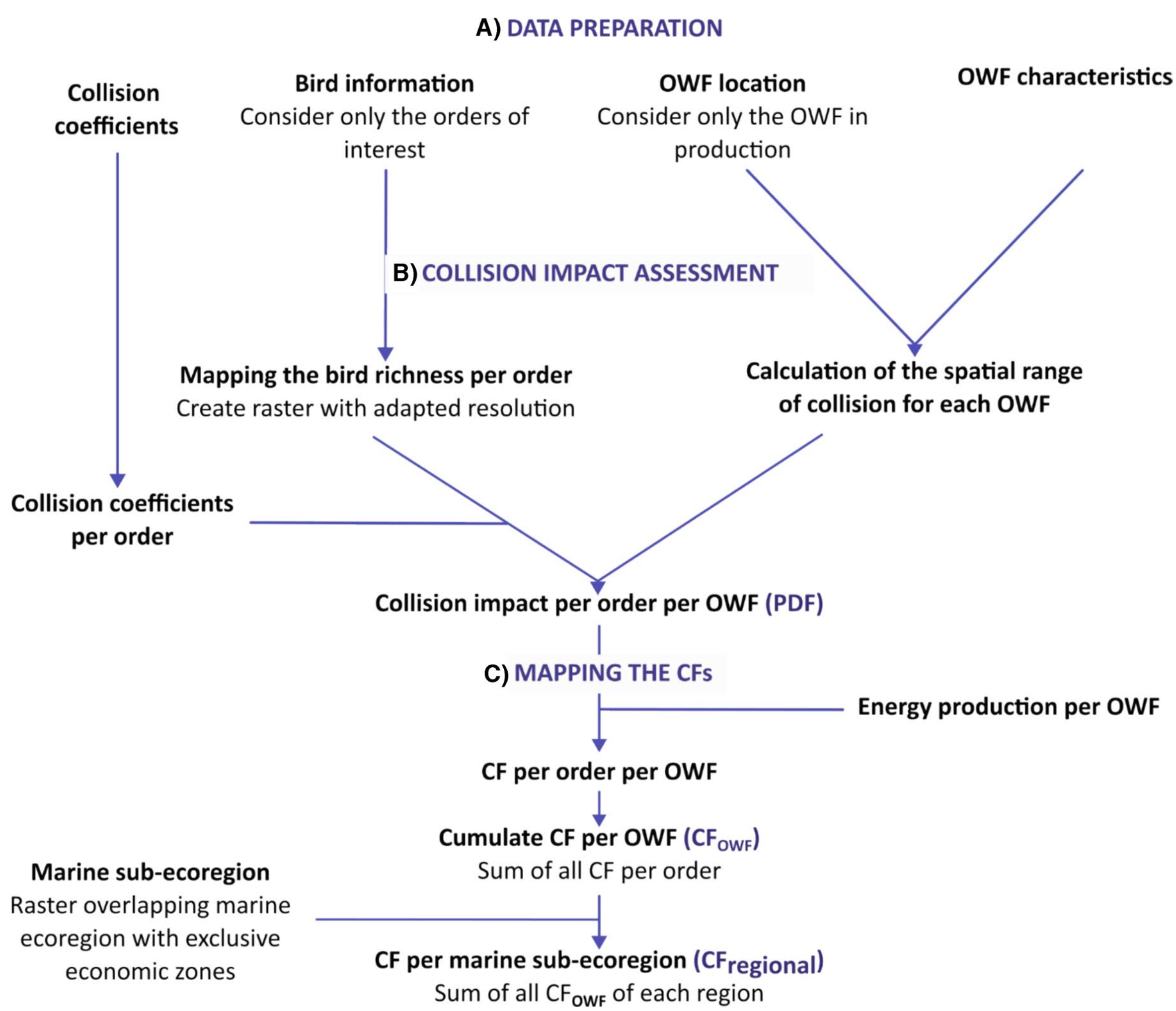

Fig. 2 Construction tree of the collision impact (PDF) and characterization factors indicators (CF_{OWF} and $CF_{regional}$)

To convert the collision impact into CF, the PDF was divided by the annual electricity production of each OWF. The annual electricity production, expressed in GWh, was estimated by multiplying the total production capacity (GW) by the average full load hours per year (2000 h, considering a 22% load factor). CF per order per wind farm was obtained from this process. To map the CF at each OWF's location, the CF per order per wind farm was finally summed to provide a unique CF per OWF (CF_{OWF}) (Fig. 2 C).

In addition, a $CF_{regional}$ was calculated, corresponding to the sum of all the CF_{OWF} for the different marine subecoregions. Finally, two types of maps were produced, corresponding to the CF_{OWF} and the $CF_{regional}$ for the current and future situation.

All the R code used for CFs and collision impact calculations is available in Supporting Information (SI 1 - Appendix 3). The resulting CF_{OWF} with the collision impact PDF and $CF_{regional}$ are reported in the Supplementary Information 2 and 3 in.xls format. For data protection reasons, the location (latitude, longitude) of the wind farms has been removed from these results.

2.2 Detailed step to adapt the indicators to OWF context

The following paragraphs describe the data preparation steps and the methodological choices made to adapt the indicators to the OWF context.

2.2.1 Data preparation

In terms of data (Table 1), the following elements were needed:

(1) Avifauna information about the distribution area of species, bird richness, and a collision coefficient informing the vulnerability of birds to collision impacts
(2) Information on the location and characteristics of the OWFs
(3) Spatial information on marine ecoregion and economic exclusive zones for the $CF_{regional}$

2.2.2 Choice of studied species

The "BirdLife International and the Handbook of the Birds of the World (2021) database" was used (Bird species distribution maps of the world. Version 2021.1—available on request from BirdLife), which provides species distribution for more than 17,500 species in a shapefile format. In addition, the database provides a descriptive information table containing the full name of the species, order, migration status, and conservation status (not used for calculation here).

From this database, we selected the seabird species of interest. There are five orders of seabirds: *Sphenisciformes* (penguins), *Procellariiformes* (albatrosses, shearwaters, storm petrels), *Suliformes* (cormorants, gannets, pelicans), *Phaethontiformes* (phaethons), and *Charadriiformes* (skuas, gulls, terns, auks). However, information on collision coefficients was only available for *Suliformes* and *Charadriiformes*, so we only selected these, which are the two largest seabird orders in terms of number of species, including 74% of seabirds (437 species out of 588 seabird species).

Since some terrestrial bird species, such as the *Podicipediformes* (grebes), can also be observed within littoral and coastal environments potentially occupied by OWF and they have known collision coefficients, they were included in the current analysis. Other "terrestrial species" have been observed migrating through OWFs, such as passerines and raptors (Blew et al. 2008). However, the BirdLife geodatabase 2021 did not record these species in marine environments, which did not allow the inclusion of these bird groups in this study.

We thus considered three orders: *Charadriiformes* (384 species), *Suliformes* (53 species), and *Podicipediformes* (55 species). In the calculation, the bird distributions and their possible migratory status were integrated. When a species was indicated as "resident," we assigned a probability of the presence of 1, while we assigned a value of 0.5 for "nonresidents." Already-extinct species were not considered.

2.2.3 Collision coefficient

The collision coefficient, *R* in Eq. 1, can be obtained from in situ measurements, experts' knowledge, or vulnerability indices. As mentioned previously, knowledge and in situ measurement of collision within OWF are lacking (Cook et al. 2018), and vulnerability indices are today the only source of information enabling global approaches. Garthe and Hüppop (2004) defined one of the first vulnerability indices for bird collision, considering nine parameters related to flight behavior (maneuverability, flight time, night activity), the level of habitat specialization (habitat, foraging strata, diet), and parameters related to conservation importance (population size, survival rate, sensitivity to cumulative impact with disturbance, and conservation status). This index was used in several studies, supplemented by Furness et al. (2013) and Bradbury et al. (2014), and was calculated for over 9500 species by Thaxter et al. (2017). The latter study is to date the most complete source of quantified information on avifauna's vulnerability to collisions. Some studies provided specific collision coefficients for seabirds in the context of OWF (Cook et al. 2018 and Kelsey et al. 2018), but only for 49 and 81 species respectively.

Table 1 Overview of the raw data used to model the collision characterization factors for offshore wind farms

Data	Use	Source	Corresponding parameters in formula—Fig. 1
Avifauna information			
General avifauna information and migratory status	The migratory status is used to estimate the probability of presence of bird species	BirdLife geodatabase 2020	$S \bullet P_i$
Shapefile* of bird area of repartition	Exposure information: identify the number of at-risk species per area	BirdLife geodatabase 2020	$S \bullet P_i$
Raster file* of bird richness per order**	Exposure information: identify the number of at-risk species per area	Created based on the combination of spatial bird richness per species	$S_k \bullet P_{k,i}$
Collision coefficient per species	Vulnerability information: intensity of potential pressure	Thaxter et al. (2017)	R
Universal species-area relationships	Extrapolate species-area relationship across continents	Storch et al. (2012)	z
OWF information			
Shapefile* of OWF location and OWF's name	Obtain a detailed information per OWF	The Wind Power database 2021 (Windfarms)	w,i
Number of turbines	Impact intensity depends on the number of turbines	The Wind Power database 2021 (Windfarms)	t_w
Total power of the OWF	CF calculation	The Wind Power database 2021 (Windfarms)	E_w
Size of turbine rotor	Impact intensity depends on the size of the rotor	The Wind Power database 2021 (Turbines)	r^2
OWF status (planned, approved, construction, operation, dismantled)	Consider potential future impacts	The Wind Power database 2021 (Windfarms)	Used for actual and prospective approach
Spatial information			
Spatial resolution = 2500 km^2 **	Effect proportional area conversion. Correspond to the spatial resolution of raster data	Chosen to limit calculation times	A_{org}
Raster file* of marine ecoregion***	Provide the extent of the regional analysis	World Working Group (Spalding et al. 2007)	Used for $CF_{regional}$
Raster file of economic exclusive area of countries***	Provide the extent of the regional analysis	Flanders Marine Institute (2019)	Used for $CF_{regional}$

*In digital mapping, the files used to identify the elements constituting the map were based either on vector files, shapefile, which are straight line segments with fixed coordinates at their ends, or by raster files, which identify elements according to recognized pixels line by line across the entire surface (Brunet et al. 1992)

**Spatial resolution was 0.8 geographic unit in EPSG4326, WGS 84, which corresponds to projected pixels of a mean size of 25,025 km^2 for the whole world (projection: EPSG:3395 World Mercator) and approximately 5400 km^2 for the regions of interest—UE and East Asia

***Spatial resolution was 0.4 geographic unit in EPSG4326, WGS 84. This corresponds to projected pixels of a mean size of 5900 km^2 for the whole world (projection: EPSG:3395-World Mercator) and approximately 2500 km^2 for the regions of interest—UE and East Asia

For this reason, and analogously to May et al. (2020a), the Thaxter et al. (2017) database on estimated collision coefficients was used. Thaxter et al. (2017) based their estimation on a literature review of studies measuring collision casualties around wind turbines, enriched by the consideration of species traits, estimating the avoidance capacity of each species.

They based their estimation on a complex three-step process: i) a literature review of worldwide collision observations, ii) a statistical analysis to determine the importance of several species traits in collision impact, such as: morphological characteristics (size, wingspan), flight maneuverability (via a Kipp distance measurement), habitat and feeding preferences, migratory status, iii) an extrapolation to a large number of species on the basis of relationships between phylogenetic traits. As a result, the collision coefficient corresponds to the collision rates per species per year.

2.2.4 Offshore wind farm data

The following information is needed from OWF for the CF calculation: the location of the wind farm, the number of turbines, the total power of the wind farm, the status of the project (planned, approved, under construction, in operation, dismantled), and the rotor size of the turbines.

"The Wind Power database" *(version: December 2021)* lists 740 OWF projects over the world. Only OWFs with known location, number of turbines, total power, and status of the project listed in the database were kept in the analysis. In turn, the analysis focused only on OWFs in Europe and Asia, as information on power or number of turbines was missing for OWF in other continents (except for two OWFs in North America, for which information is provided in the Supplementary Information 2). OWFs that were dismantled or located in large lakes were removed from our selection, to only focus on current and future situations at sea. Subsequently, we included 226 OWFs currently in operation for the analysis of the current situation, and added 181 OWF projects that are planned, approved, or under construction to test a prospective approach.

In addition, a second database from the same provider *("turbine database," version: December 2021)* was used to complete the missing information about the turbine model, rotor diameter, and rated power per turbine. However, the rotor diameter was only provided for 23% of the turbines. For the wind turbines that had missing information, the rotor diameter was estimated by applying a logarithmic function between the rated power and the length of the turbines as in May et al. (2020a).

2.2.5 Spatial data and resolution for CFOWF and $CF_{regional}$ analysis

We only modeled the bird collision with the turbine and did not consider the potential impacts due to high-voltage lines linking OWFs at the grid system. The CF model is based on calculations carried out with raster spatial data at sea. The resolution of these raster files determines the calculation times and must be adapted to the extent of the wind farms to avoid potential double-counting. May et al. (2020a) used raster data with 1-km resolution (1 km^2), which is sufficient to calculate the CF of onshore wind farms, but which is too small for OWFs and generates calculation times over 10 days. A lower resolution of about 50 km (raster data with pixels of 0.4 geographic units in the WPS84 geographic coordinate system—2500 km^2) was then selected. This resolution seemed to align well with the surface of the OWFs currently in operation and reduced calculation times to 5 days.

With the QGIS software 3.20 Odense, the necessary geographic layers were converted into raster files of this resolution (resampling technique: nearest neighbor), including the raster file of bird richness per order, as well as raster data of the exclusive economic zones of each country, and the marine ecoregions (Table 1), necessary for the $CF_{regional}$.

The maps of the exclusive economic zones were taken from the Flanders Marine Institute (2019) and the marine ecoregions from the Marine Ecoregions of the World Working Group (Spalding et al. 2007). To maximize the level of detail of the $CF_{regional}$, "marine sub-ecoregions" were created by dividing marine ecoregions into different areas according to the exclusive economic zones, using the "joint tool" in QGIS software. This makes it easier to identify priority marine areas within smaller regions, such as in Europe, where OWFs are highly concentrated in the North Sea and inside the exclusive economic zones.

2.3 Testing the developed indicators

2.3.1 Analysis of the parameters influencing collisions

We tested the variation of the collision impact considering the location of the OWF (continent and shore distance), the technical characteristics of the farms (total power, number of turbines, length of the blades), and the different bird orders.

To do so, we conducted a principal component analysis (PCA). PCA is a statistical method for exploration and dimensionality reduction in quantitative multivariate data. It transforms the original variables into a set of linearly uncorrelated variables called principal components, ordered by the amount of variance they explain. The goal is to capture the essential information in the data with fewer dimensions, making it more manageable and facilitating pattern recognition. Each principal component is associated with an eigenvalue, which represents the amount of variance explained by that component. Higher eigenvalues indicate more important components. The loadings of each variable on the principal components provide information about the contribution of that variable to the component. Larger loading values signify a stronger influence. Graphical representations, such as correlation circles and individuals plot, visually elucidate the relationships between variables and individuals in the PC space. The squared cosine of the variables represents the quality of the representation of the variables on the PCA graph.

All of the PCA functions used here were present in the R package "FactoMineR," and the final R code is available in Supplementary Information 1.4.

2.3.2 Application example

LCA is used in comparative studies to support the selection of environmentally preferable alternatives (Verones et al. 2017). Comparisons can be made for example between different products with the same function and functional unit, different life cycle stages of a product system, or between different types of impacts. As a very simple application example of the indicator developed, the collision impact calculation was applied to two OWFs in France, and the results were compared with the climate change impacts during the operation phase. The two OWFs are the "Fécamp OWF" in the English Channel (498 Megawatts, 83 gravity-type turbines), which is planned to be operational in 2024, and the "Yeu-Noirmoutier" in the Atlantic, planned to be operational in 2026 (Fig. 3). Both are planned to be operational for 25 years. These two OWFs were chosen because information on the overall carbon footprint of the projects was available and can be used for further comparison with the collision impact (BRL Ingénierie 2008; Dong Energy et al. 2013). The functional unit used for these carbon footprint assessments is the production of 1 GWh of electricity. According to other LCA studies for OWF projects (e.g., De Luca Peña et al. 2023; Lehmann et al. 2024), the system boundary includes all of the components of the OWF at sea (turbines, foundations, cables, sub-station at sea) and the onshore high-voltage station. All the life cycle stages of an OWF project are considered: raw material extraction, component assembly, OWF construction at sea, operation and maintenance (including the environmental impact of equipment replacement and the use of vessels for plant maintenance), decommissioning, and potential valorization of the materials. Some studies, like in the case of the Yeu-Noirmoutier LCA (BRL Ingénierie 2008), also consider emissions connected to energy for maintenance buildings, replacement of IT equipment, and transportation of all personnel working on maintenance buildings.

Given the extensive range of environmental impacts covered by the LCA of an OWF project, it becomes essential to apply specialized methodologies to harmonize distinct impact indicator units and compare them. We chose the LC-IMPACT methodology to facilitate the transformation of the carbon footprint's midpoint indicator, typically quantified in CO_2 equivalents, into an endpoint indicator, as detailed by Verones et al. (2020). Such conversion allows for a direct comparison with collision impacts, which are expressed as an endpoint LCIA indicator in PDF.year.

The estimated emission of greenhouse gas was translated to PDF.year (Eq. 1) by considering a temperature factor, describing the temperature change in degrees caused by the release of one kg CO_2 over a 1-year period (corresponding to $4.76e^{-14}$ °C.year/kg CO_2) (Shine et al. 2005) and an effect factor, which is 0.037 PDF/°C (Urban 2015).

IMPACT (PDF.year) = greenhouse gas emission in kg CO_2 eq × temperature factor × effect factor(1).

To enhance the comparability of the two impacts, we include the global carbon footprint data for the OWF in our results. A comprehensive breakdown of the carbon footprint, as well as a comparative analysis with collision impacts at

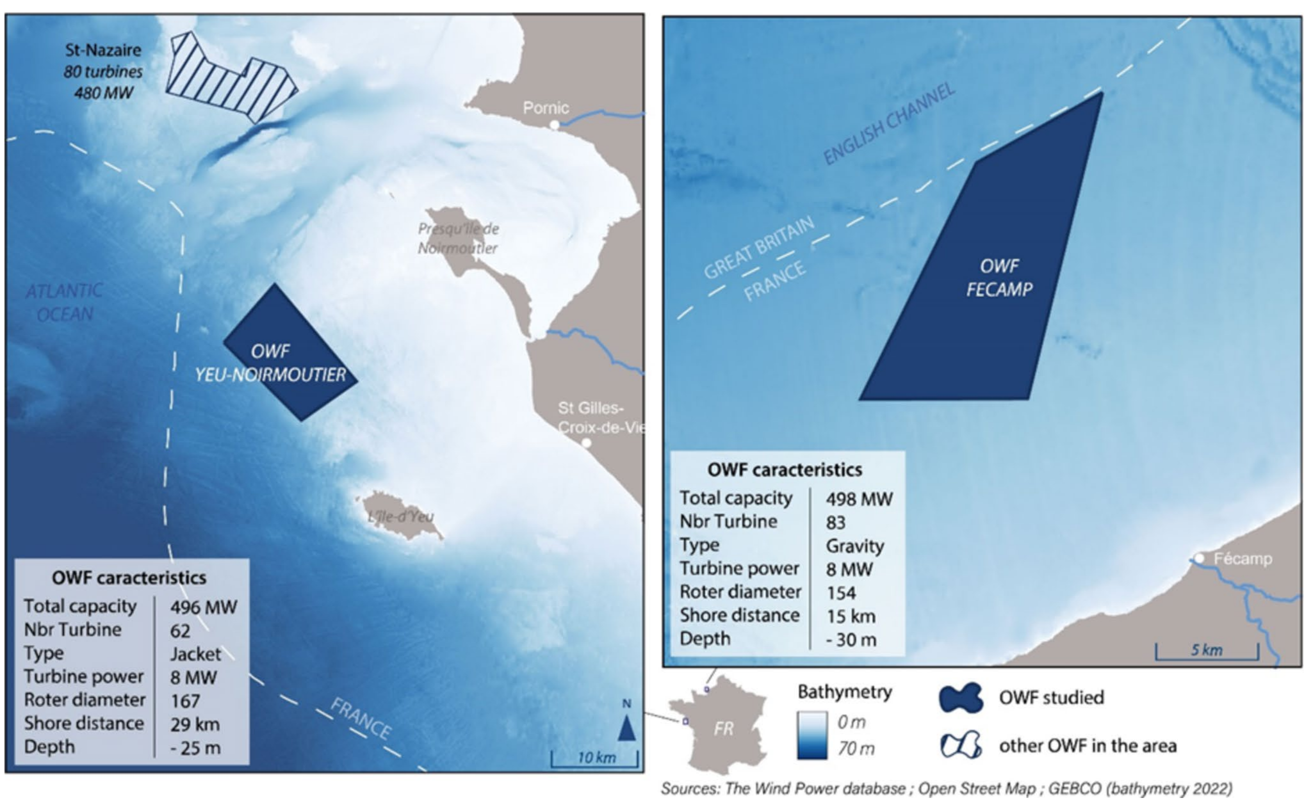

Fig. 3 Location of the OWFs used to apply the collision characterization factor to two specific case studies

each life cycle stage for both case studies, is detailed in Supplementary Information 1.6.

3 Results

3.1 Current and future evolution of collision impacts of OWF

CF_{OWF} for bird collisions with existing OWFs exhibits regional variations. Specifically, it averages at $1.05e^{-14}$ PDF.year/GWh (min = $2.0e^{-15}$, max = $1.31e^{-13}$ PDF.year/GWh) in Europe, while in Asia, the average CF is higher, standing at $3.43e^{-14}$ PDF.year/GWh (min = $1.0e^{-15}$, max = $6.9e^{-14}$ PDF.year/GWh) (Fig. 4 and Supplementary Information 2 for details of the results). In Europe, mainly in the North Sea and the Baltic Sea, there is a higher number of OWFs than in Asia (135 OWFs in Europe in our calculation, 76 in Asia), but with a lower CF_{OWF}. This is confirmed if we compare the CF_{OWF} of all OWFs studied (Supplementary Information 2). Indeed, among the 50 OWFs with the highest CF_{OWF} out of the 226 in actual exploitation, only three are located in Europe and 42 are located in China (the others are in South Korea, Japan, and Taiwan). The three highest CF_{OWF} are located in Sweden, China, and South Korea.

Since CFs are quantified relative to the functional unit, larger OWFs result in lower CFs due to their increased energy production. Consequently, for an equivalent power output, the potential impact of collisions is expected to be greater in Asia than in Europe, reflecting higher production capacities in Europe. Considering the $CF_{regional}$, the values range between $0.02e^{-13}$ and $0.07e^{-13}$ PDF.year/GWh (Fig. 4). The highest values are found in China, the UK, Sweden, Germany, South Korea, and the Canary Islands (see Supplementary Information 3 for the results of all regions and Supplementary Information 1.7 for a synthesis of the main $CF_{regional}$).

Analyzing the results for future OWFs planned worldwide, we find that the average CFs stand at $3.0e^{-14}$ in Europe (min. = $3.0e^{-15}$, max. $1.06e^{-13}$) and $4.4e^{-14}$ in Asia (min. = $2.0e^{-15}$, max. = $1.69e^{-13}$). This represents an increase in the average CF by + 182% in Europe and + 28% in Asia, suggesting a potential rise in collision risk in the future.

To explain this rise, a detailed analysis of the results by region (refer to Supplementary Information 2 and 3) indicates that the development of future OWF in areas with estimated high-collision risks is a significant factor, like in Yellow Sea, East China Sea, Azores, Canaries, Madeira, and the South European Atlantic. In addition, there are plans for new OWFs in new areas of the world where the risk of collision is expected to be particularly high, especially in Europe in the Adriatic Sea and the Ionian Sea (Mediterranean Sea). As a result, we observe an increase in the $CF_{regional}$ in nearly all regions. This indicates a potential for significant collision impacts in the future and underscores the critical need to consider inter-regional variability when managing the bird collisions with OWF.

3.2 Identification of parameters influencing collision impact

This section extends the analysis beyond geographic variability to assess how parameters of energy production may influence collision impacts. Given that the CF is a function of energy production, represented as PDF.year/GWh, an unnormalized indicator is necessary to estimate the impact of variables that determine energy production, such as turbine number or size. Consequently, this section provides an analysis of collision impacts associated with OWF, quantified as PDF.year.

PCA analysis allows us to identify the parameters that explain the variability of the results and those which most influence the collision impact. One correlation circle and the individuals plot were produced on Dimensions 1 and 2, which explain 78.5% of the results (Fig. 5). The analysis was confined to these two dimensions, as the inclusion of additional dimensions did not substantially explain further variability (Supplementary Information 1.8.1 to 1.8.3). In these two dimensions, the $\cos^2$ of each variable, representing the quality of their representation, lies between 0.5 and 0.9, with the parameter "turbine diameter" being the least well-represented.

First, we observe a strong correlation between the electricity production, the cumulative impact, and the impacts on *Suliformes* and *Charadriiformes* species (Fig. 5A). This implies that the highest collision impact is observed in OWF with greater production, a factor correlated mainly with the number of turbines rather than their diameter. To a lesser extent, collision impact is correlated to the distance to shore. Based on our dataset and indicators, these results indicate that the most effective strategy for managing collisions appears to be, in order of priority, reducing the number of turbines, then minimizing their size, and finally, situating the OWFs farther from the coastline.

Furthermore, the PCA indicates that there is no significant link between species richness and the collision impacts as determined by our indicators. The CF and impact indicators assess the risk of species extinction by considering the vulnerability of the species involved, regardless of their diversity. This result brings to light the potential for further development of our indicators, aiming for a more comprehensive incorporation of the species richness parameter.

Analysis of the individuals plot (Fig. 5B) reveals regional disparities. The scatterplot for OWFs in Europe is widespread along the Dimension 1 axis, meaning that European OWFs are diverse in terms of total production and collision

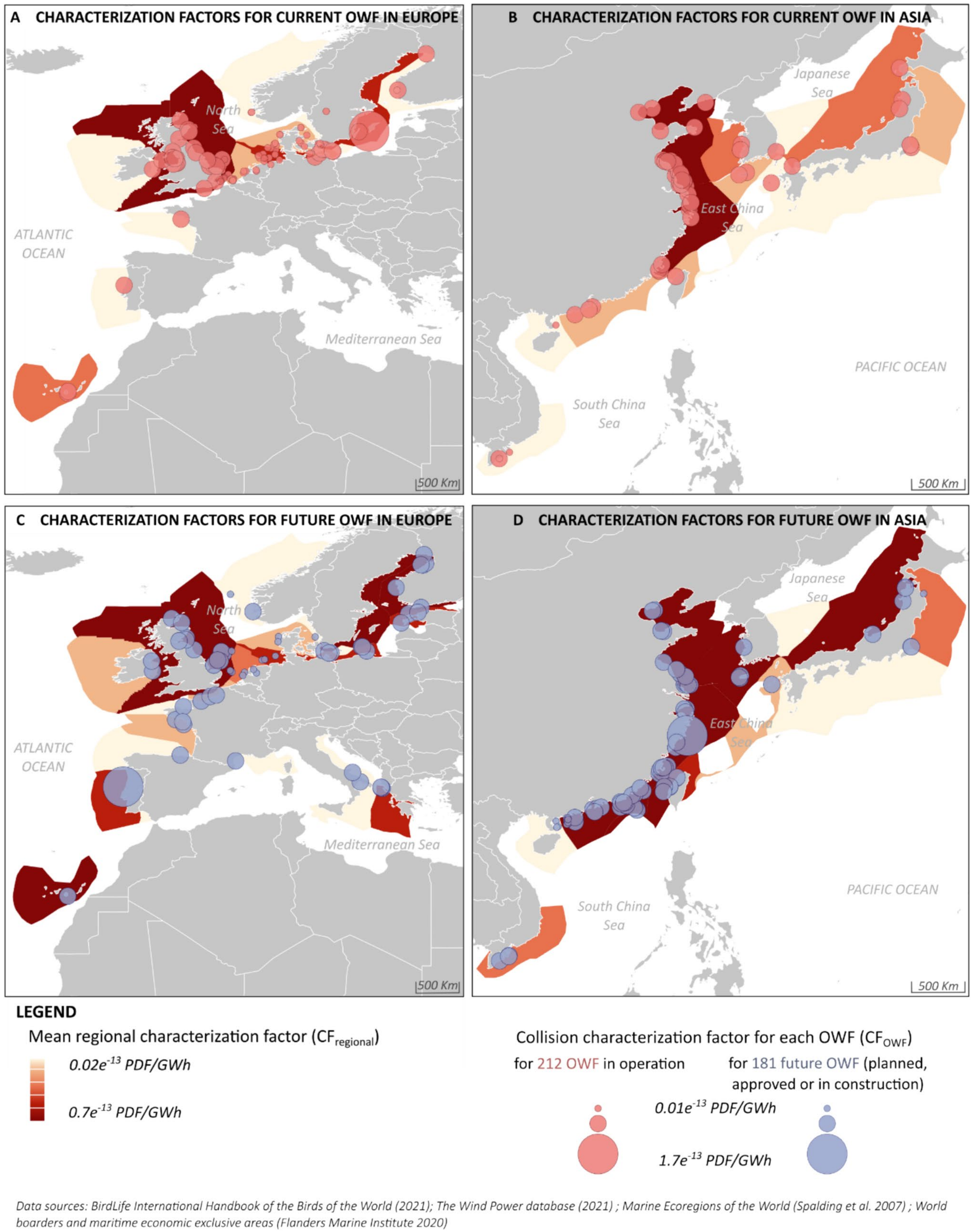

Fig. 4 Mapping of the actual CF_{OWF} and $CF_{regional}$ in Europe (A) and Asia (B) and for the predicted situation in the same continents (C and D) considering OWF projects in construction, planned, and approved

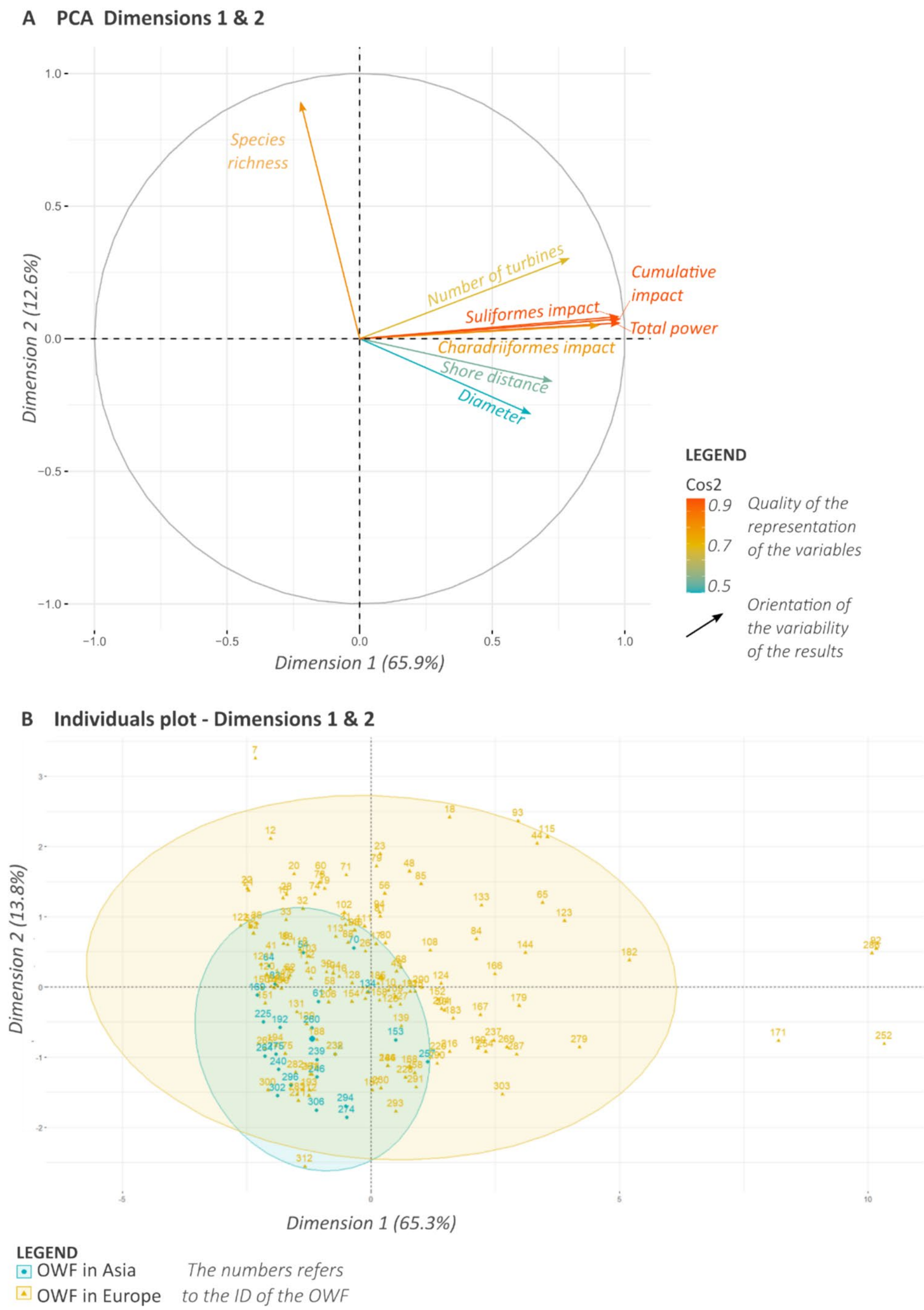

Fig. 5 Results of the principal component analysis (PCA) and individuals plot to represent the variability of the results

impact but concentrate on the farms with the highest collision impacts. For example, the highest potential collision impact is calculated for the Hornsea project 1 to 4 and Dogger Bank A, B, C project, two OWFs located off the Norfolk and Yorkshire coasts in the UK, and considered the biggest OWF projects in the world (more than 300 turbines each and producing between 2.4 and 3.6 GW), with respectively a collision impact of $1.9e^{-8}$ PDF.year (CF = $7.1e^{-14}$ PDF.year/GWh) and $1.8e^{-8}$ PDF.year (CF = $4.1e^{-14}$ PDF.year/GWh). The flattened shape of the European ellipse indicates that the variability of European OWF is not well explained by this axis, i.e., by the species richness. On the other hand, the scatterplot for OWFs in Asia appears in the lowest part of Dimension 1, indicating OWFs with lower impact in terms of collision, and smaller farms with less production and turbines. The shape of the ellipse seems to be drawn by the Dimension 2 axis associated with species richness (Fig. 5B), but this is largely due to a single farm in Asia (Xidao OWF, off the Taiwan coast), which has a bird richness much higher than the others represented in the analysis (a species richness of 100 in this particular farm for a mean species richness of 36 in the analysis). We tried to carry out the PCA again by removing Xidao OWF from the analysis (the original PCA is available in Supplementary Information 1.8.4). Without this OWF, it appears that European OWFs have a more homogeneous repartition on Dimension 2, and that on average, Asian OWFs host a lower bird richness.

3.3 Application example to two French OWF projects

To compare the impact of collisions with the carbon footprint, the latter was converted in an endpoint impact and the collision impact was expressed in PDF_{25yr}, corresponding to the PDF.year for the operational life of the OWF studied, which is 25 years.

The global carbon footprint corresponds to 636,638,000 kg CO^2 Eq. ($1.12e^{-06}$ PDF after conversion) for Fécamp OWF and 705,592,000 kg CO^2 Eq. ($1.21e^{-06}$ PDF after conversion) for Yeu-Noirmoutier OWF, while the collision impact is evaluated at $2.58e^{-07}$ PDF_{25yr} and $1.92e^{-07}$ PDF_{25yr}, respectively (Table 2). By summing the two impacts, the total relative impact corresponds to $1.38e^{-06}$ PDF for Fécamp OWF and $1.41e^{-06}$ PDF for Yeu-Noirmoutier OWF. Based on this calculation, the collision impacts contribute to 18.72% of the total relative impact for Fécamp and 13.62% for Yeu-Noirmoutier. The difference between the two evaluations is linked to the method used to calculate the carbon footprint for the two case studies. In the Fécamp OWF estimations (Dong Energy et al. 2013), only the transport linked to the maintenance was considered to calculate the carbon footprint of the operational phase, whereas the study of the Yeu-Noirmoutier OWF (BRL Ingénierie 2008) also considers the energy consumed by the maintenance building and the replacement of computer equipment.

The findings reveal that the net effect of impacts associated with climate change from the two case studies are about six times higher than the net effect of collision impacts comparing the collision impact with the global warming impacts provides a reference point to better interpret the collision impact assessment results.

4 Discussion

The development of large-scale OWFs involves biodiversity impacts that are currently not accounted for in LCA (Arvesen and Hertwich 2012). In this study, we have focused on the potential impacts on birds due to collision in the operational phase of OWFs. Three indicators adapted from May et al. (2020a) are provided: (1) a characterization factor for LCA (CF_{OWF}) expressed in PDF.year/GWh, mapped for each OWF worldwide to estimate the potential loss of bird species in response to collision; (2) a specific $CF_{regional}$ expressed in PDF.year/GWh to estimate the mean collision CF at the scale of marine ecoregion; and (3) a collision impact, expressed in PDF.year that is used to statistically analyze the parameters influencing collisions. The final maps, presenting actual and future situations, allow the identification of the most at-risk areas for bird fauna in Europe and Asia in the context of OWF development. The largest CF were found to occur in Asia with this trend predicted to increase in the future, extending to more marine areas in Europe and Asia as new OWFs are being built.

A PCA analysis reveals the parameters that could explain the variability of the results and most influence the collision impact. The PCA identified the OWF total power as the main parameter, followed by the number of turbines, the blade length, and the shore distance.

This article yields contrasting findings from two distinct indicators: the CF, designed for an LCA application, and a collision impact indicator. The collision impacts are estimated more important in Europe, which may be attributed to the larger scale and enhanced capacity of wind farms compared to Asia. In contrast, the CF reveals a heightened

Table 2 Case study results: conversion of carbon footprint mid-term impact in end-term impact and comparison with collision impact for Fecamp and Yeu-Noirmoutier OWF

	Parameter	Unit	Fecamp (ID: 7282)	Noirmoutier (ID: 16,529)
A	*Operation lifetime*	year	25	25
B	*Collision impact*	PDF.year	$1.03e^{-8}$	$7.69e^{-9}$
C	*Collision impact operation (B*A)*	PDF_{25yr}	$2.58e^{-7}$	1.92^{e-7}
D	*Global carbon footprint*	Kg CO_2 eq	636,638,000	705,592,000
E	*LC-Impact (converting t CO_2 eq to PDF.year)*	PDF.year/kg CO_2 eq	$1.76e^{-15}$	$1.76e^{-15}$
F	*Carbon footprint converted in endpoint impact (D*F)*	PDF	$1.12e^{-06}$	$1.21e^{-06}$
G	*Total relative impact for carbon footprint and collision impacts (C + G)*	PDF	$1.38e^{-06}$	$1.41e^{-06}$
H	*Relative contribution of collision in total impact (C/G)*100*	%	**18.72**	**13.65**

potential impact in Asia, because it considers the impacts in relation to the energy production of each wind farm. The impact indicator sheds light on the wind farm parameters that influence the impact's intensity, whereas the CF indicator detaches from the technical characteristics of the farms to emphasize regional specificities, particularly the sensitivity to collisions.

Thus, the CF indicates that at equivalent power production, an OWF located in Asia would generate a higher collision impact than in Europe. We can hypothesize that this is due to the presence of species more sensitive to collisions in Asia than in Europe.

The implications of the results for research and marine spatial planning are discussed in the following paragraphs, as well as the limitations of our study and some perspectives on future research.

4.1 Application by LCA practitioners

The present study proposes a first set of CFs for LCIA, to consider the impacts of operational OWFs on biodiversity. Two indicators, compatible with LCA spatial assessments, were proposed to estimate the potentially disappeared fraction of bird species sensitive to collisions with OWFs.

The developed CF_{OWF} and $CF_{regional}$ correspond to LCIA endpoint indicators for the assessment of the "ecosystem quality" protection area (Hauschild and Huijbregts 2015). The CFs are compatible with LC-IMPACT (Verones et al. 2020) or ReCiPe (Huijbregts et al. 2017) methods and provide information to assess the LCIA impact category relative to "marine biodiversity loss." However, although impacts on avifauna are among the main biodiversity impacts of OWF, other impact models could be developed to enrich the assessment of the "marine biodiversity loss" impact category (some examples are discussed in Sect. 4.4). Nevertheless, our indicators can be used directly to compare different impact categories, such as global warming, as proposed here for two French OWFs. Such an approach makes it possible to identify the importance of one or more impacts in relation to another and to better perceive the importance of collision impacts.

Beyond classic LCA use, it would be possible to estimate the collision risk of a specific OWF if the engineering information is known (OWF location, total power, turbine number, and rotor size). Two assessment approaches are possible:

1. Using the $CF_{regional}$ of the marine sub-ecoregion where the OWF is located and multiply it with the OWF's total power. This approach would provide a quick estimation of the collision impact potential but would not be very precise.
2. If in situ spatial bird diversity data are available, it would be possible to apply the code provided in Supplementary Information 1.3 to calculate the collision impact on a given territory. This approach needs to identify the bird species locally present and characterize their collision coefficient using a collision index such as those proposed in some of the studies in Supplementary Information 1.2. Such an approach would provide a high level of accuracy and reliability of collision impact assessment.

4.2 Implications of the results for research on the impacts of offshore wind

The manufacturing of the components and recycling phases of wind turbine components have been the only life cycle phases studied so far in LCA for OWF (Arvesen and Hertwich 2012). Our approach provides one of the first assessments of the ecosystem impacts on the biodiversity of OWF during the operational phase. The CF indicators produced are spatialized, showing that life cycle impact assessments can highlight the spatial impacts of specific pressures. It also gives species-specific information and insights regarding potential factors increasing collision impact. Among these factors, the influence of the total power of the farms, number of turbines, shore distance, and blade length were checked with a PCA approach. These parameters were chosen because some studies consider them as the main ones influencing the collision impact of OWF (Dierschke et al. 2016; Skov et al. 2018).

The PCA emphasizes a hierarchy of the tested parameters to collision and a geographical variability of the impact across Europe and Asia. The OWF total power influences collisions the most. Some regions that have significant annual OWF electricity production, such as China, the Baltic Sea, and the UK, were also found to have high-collision CFs (Supplementary Information 1.7 and 2).

In addition to the production capacity of the farm, the number of turbines and the length of the blades are other important factors. It is known that production capacity is correlated to these two factors, but we observe a potentially higher influence from the number of turbines than the length of the blades, suggesting that it is preferable to limit the number of turbines per OWF to reduce the collision impact. The next factor influencing collision impact is the shore distance. The result here is surprising, as it shows that OWFs farther from the coast have a higher potential impact, which is contrary to the idea most often put forward that moving OWF away from the coast would reduce collisions due to a reduction in species richness (Garthe and Hüppop 2004). However, as we illustrated with the PCA analysis, species richness is not a parameter influencing our impact indicator. These results suggest that OWF located farther from the coast has a higher production capacity and contains more turbines or larger rotors, resulting in a greater potential impact. These results warn against the potential increase of the collision impact with the choice of locating OWF farther from the coast to increase their production capacity.

These results indicate that encouraging OWFs with a lower number of turbines or a lower diameter of rotors could reduce the collision impact.

Also, considering these elements highlights the need for compromise between electricity production and bird conservation. As suggested by Arvesen and Hertwich (2012) and May et al. (2021), spatially differentiated CFs developed in this work could serve to identify at-risk areas and species to be considered in environmental management, in order to reduce the global impacts of offshore wind technologies.

This is particularly important considering the collision impact of future OWFs. The prospective approach tested here identifies new regions with important stakes for bird conservation that are planned to be exploited for offshore wind energy, such as the Mediterranean Sea and the Japanese Sea. In these regions, solutions to reduce the collision risk need to be identified. The study of May et al. (2020b) suggests painting the blades of wind turbines to make them more visible, with encouraging results. Similar measures should be identified for OWF, considering the cumulative impacts of attraction and avoidance of bird behaviors and adapting them to the bird species present (Supplementary Information 1.1).

4.3 Limitations and uncertainties

The collision indicators presented in this paper have three main limitations, relative to the quality of the collision coefficients used, the level of generalization required to calculate CFs, and the limited number of considered bird species.

The collision coefficients used are important for the calculation of the collision CF_{OWF} and $CF_{regional}$, but are subjected to some biases. Some are already identified by Thaxter et al. (2017), like the heterogeneity in the data sources used to calculate the collision coefficient by species, since biodiversity sampling tends to be expensive and conducted in high-income countries, in northern latitudes.

As the data used are derived from measures conducted on land, when applied to offshore environments, some variability of the collision impacts could be expected. In OWF contexts, the implementation of artificial reef structures alters bird-habitat relationships by creating new feeding areas, resulting in increased attraction effects (Dierschke et al. 2016—Supplementary Information 1.1). Unfortunately, the impact of the reef effect on bird populations has not yet been quantified (Blew et al. 2008; Dierschke et al. 2016). OWF impacts on bird should be addressed with a cumulative impact assessment perspective. Moreover, the knowledge base on the risk of collision with OWFs is extremely limited (Cook et al. 2018), and general knowledge on seabirds, such as ranges, is still lacking for certain regions of the world, like North America (Goodale et al. 2019). Furthermore, bird collisions with OWFs are likely to occur less frequently than with onshore installations, as birds can better detect the structures from greater distances at sea (Blew et al. 2008). Also, most studies show that birds avoid the OWF, which limits the risk of collision (Leemans and Collier 2022; Skov et al. 2018). Considering these parameters, it is conceivable that the calculated CFs and impacts might be understated or, conversely, overstated if the reef effect exerts a significant bird attraction. More studies on the specific behaviors of bird species are needed (Cook et al. 2018; Marques et al. 2014).

Another important bias is the low consideration of the bird's flight altitude in the estimation of the collision rates per species (Garthe and Hüppop 2004; Jongbloed 2016). Thaxter et al. (2017) consider the flight altitude towards the foraging strata parameter (if the species feed at water surface, at land surface, in the tree, or in the air in altitude). However, as mentioned before, foraging strata could evolve with the reef effect and would be different at sea. Also, as *Podicipediformes* generally have a low flight altitude, it is likely that most species in this order have a low probability of collision with wind turbines. This is why the collision impact on this order was not integrated in the PCA analysis.

Improving data on birds' flight altitudes would broadly improve our model. Some studies consider the flight altitude in their collision coefficient estimations, as in Furness et al. (2013) and Garthe and Hüppop (2004).

Another bias refers to a classic limitation of LCIA, relating to the high level of generalization that this approach requires. The CFs are calculated and averaged for each bird order, but within the same order, species can have different behaviors and traits, which would lead to variability in collision impacts. Also, ecological characteristics like age, sex, and environmental conditions that strongly influence the distribution of seabirds are not considered (Petersen and Malm 2006). In future studies, the migration status should be better considered by assigning, for example, a coefficient related to the number of months of presence within an OWF site. Models of presence probability or collision rates calculated with measured field data would also improve the assessment.

Finally, while the CFs are calculated for 437 species, representing 74% of marine birds, allowing to identify trends, information about other species observed in OWF areas is lacking, including terrestrial migratory birds. In France for example, out of the total number of migratory birds found in the coastal environment, 172 species are terrestrial birds 126 shorebirds, and 28 raptors (Kirby 2010), which could represent a slight increase in collision if these birds are flying at the blade altitude.

4.4 Outlook to improve LCIA of OWF

The different limitations of the approach and the barriers to the development of offshore wind impact indicators are all potential areas of research to improve the LCIA of OWFs.

There are still significant barriers to the development of a comprehensive LCIA in the context of the OWF. First, there is a lack of accurate and quantitative information about most of the impacts generated by OWF (Dannheim et al. 2020). Even if the feedback from OWF deployed in the North Sea increases knowledge of the environmental impacts of OWFs (e.g., Degraer et al. 2019), numerous questions remain, for example, regarding the extent of deterring bird or marine mammal populations (Dierschke et al. 2016; Le Visage et al. 2021), or the influence of electromagnetic fields on magneto-sensible species behavior (Degraer et al. 2020; Skov et al. 2018). The processes involved are highly variable and complicated to fully integrate into LCIA, and they also differ remarkably between the different phases of the life cycle of the farms (Baulaz et al. 2023; Brignon et al. 2022). Dannheim et al. (2020) argue for example that the artificial reef effect, i.e., a process that provides a habitat for marine biota resulting from the submergence of anthropogenic structures placed deliberately or accidentally on the sea (Mavraki 2020), is considered the main ecosystem impact of OWF, occurring only during the operation phase. For the construction phase, the sounds and vibrations generated by the implementation of infrastructures in the sea, notably considering fixed bottom monopile OWF, are the main effects (Bergström et al. 2014). All these aspects differently affect species depending on their sensitivity or life traits.

In addition, the co-occurrence of OWF effects can lead to poorly understood cumulative effects that can affect the entire ecosystem through trophic cascades and other processes (Burkhard and Gee 2012; Le Visage et al. 2021). This is increased by significant data gaps on the functioning of marine ecological dynamics in general (Galparsoro et al. 2012; Kéfi et al. 2019). Regarding birds, it seems that the impacts related to the loss or modification of habitats may be more significant than the impacts related to collisions, despite the lack of comprehensive information to confirm it. This result is particularly evident for certain species such as the Northern Gannet (Garthe et al. 2017), but it appears to vary greatly from one species or study to another (Leemans and Collier 2022). This suggests that it would be interesting to develop an approach to consider the other indicators proposed by May et al. (2020a) in LCA to assess the impact of disturbance and habitat loss due to OWFs on birds.

To improve the results at the local scale and to overcome the lack of information, precise data on the distribution, abundance, and diversity of species, as well as collision coefficients with OWFs, are needed. The effects of OWFs vary greatly across space. Taking the spatial dimension into account is crucial in order to establish trade-offs between offshore wind development and conservation (Punt et al. 2009). If accurate turbine locations and species datasets were available, it would be possible to calculate turbine-scale CFs and thus provide important information on the relationship between turbine location and impacts on biodiversity. Supplementary Information 1.1 provides some information about the different effects of OWF on bird species that could be integrated in environmental impact assessment for developing future indicators for LCA. Precise information on electricity production would also improve the calculation. For example, we considered a full load hour of 22%, but technological advances in OWF would improve this load factor. This is important to calculate the annual electricity production of the OWF; Arvesen and Hertwich (2012) recommend using a 43% load factor for OWF.

Beyond the impacts on birds, the disturbances generated by OWF affect all trophic groups, and LCIA indicators to assess each of these specific impacts are needed. In particular, it would be interesting to consider expressing impacts in terms of "potentially affected fraction of species," which would make it possible to integrate species richness influence. This approach would be particularly interesting for certain impacts linked to habitat modifications. However, one of the specificities of the impacts of offshore wind energy compared to other energy sources is the potential increase in biodiversity linked with the reef effect in some locations (Dannheim et al. 2020). Specific indicators like a "potentially aggregated fraction of species," considering the potential gain in biomass in LCIA, are to be developed. A recent study proposed a joint assessment of the "footprint" and "handprint" in the LCA of an OWF project, considering both the negative and positive impacts generated by the structures on the ecosystems and the human well-being (Van de Pol et al. 2023).

Furthermore, our application to the French case studies allowed us to compare the impact of collisions with the effects of global warming—an impact category commonly considered in LCA. This approach enables broader interpretations of our results and facilitates the integration of biodiversity impacts into LCA research.

Moreover, in the context of developing a standardized LCIA, it is crucial to establish clear conceptual and methodological models (Hauschild and Huijbregts 2015). These models should include precise definitions of disturbance and mechanisms affecting populations. Specifically, they should account for the potential variation in pressure type and intensity associated with different offshore wind turbine technologies. Factors such as the type of foundation used, the geographical context, and the presence of specific species all play a role in shaping the impacts of OWF on the environment (Le Visage et al. 2021).

5 Conclusions

Life cycle assessment (LCA) is a widely applied method to characterize the environmental impacts of offshore wind farms (OWF). Despite its usefulness, some key indicators are still presently missing to cover all the impact pathways of these and other energy systems, including impacts on biodiversity. For OWF, none of the ecosystem impacts in terms of biodiversity loss arising from the construction, operation, and dismantling phases of the OWF is typically considered in LCAs. Due to the worldwide development of marine renewable energies, developing the most reliable and complete LCA possible has become a major issue. The present study aims to overcome, in part, this issue by proposing a first set of characterization factors (CFs) for life cycle impact assessment to consider the impacts of operational OWFs on biodiversity. Three indicators, compatible with LCA spatial assessments, were proposed to estimate the potentially disappeared fraction of bird species sensitive to collisions with OWFs. The indicators are tested using bird species richness data and the location and characteristics of OWF data. The databases used allowed us to estimate the impact in the current situation and in the future, while calculating the CFs for planned or under-construction OWF projects. The OWFs and maritime regions with the highest impacts were identified, and the estimation of the evolution of the collision impacts in the future is calculated. Different factors including the total power of the farm, the number of turbines, the shore distance, and the diameter of the rotors were also evaluated to identify the main factors influencing bird collision impacts in our dataset. Finally, an approach was tested to compare the collision impact with those of a well-known LCA impact category, namely global warming.

The results of this study are essentially methodological, but they also provide some operational information, mainly related to the comparison of bird collision impacts depending on the different geographical areas and the identification of parameters determining the impacts. This information may be valuable to inform decision-makers by identifying the most at-risk areas for birdlife, species-specific impacts, and the parameters to be considered to reduce impacts and improve marine spatial planning in the context of marine renewable energy development.

6 Results availability

The results of the collision CF_{OWF} and impact for operational OWF and future projects are provided in the Supplementary Information files. Nevertheless, for data privacy reasons, the latitude and longitude information of the offshore wind farms are not provided. The results of the $CF_{regional}$ are provided in full in the Supplementary information files.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-024-02413-8.

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Data availability The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding authors upon reasonable request. Data are located in controlled access data storage at the Norwegian University of Science and Technology (NTNU). Commercial use of the bird species distribution maps of the world data or of derived products incorporating them is not permitted. Potential commercial users can access these data via https://www.ibat-alliance.org/.

Code availability R code to calculate the characterization factors described in this paper and R code to realize the PCA to identify principal parameters influencing collision impacts are provided in the Supplementary Information files.

Declarations

Competing interests The authors declare no competing interests.

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