Federal Policy Research

Final report

IMPACT OF SOUND ON MARINE ECOSYSTEMS FROM OFFSHORE WIND ENERGY GENERATION | PURE WIND

RT/22/PUREWIND

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STUDY A – CHARACTERISATION OF UNDERWATER SOUND RADIATED BY OPERATIONAL WIND FARMS FOUNDATION FIXED TO THE SEA FLOOR. THE BELGIAN NORTH SEA CASE.

Abstract

The Belgian zone of the North Sea is a maritime domain that hosts many anthropogenic activities. A zone of energy production situated next to the border with the Netherlands includes just under 400 wind turbines today, with about 2,26 GW of installed power. All parks are operational. Rotating wind turbines are generating underwater noise that needs to be characterised. PUREWIND objective is to characterise operational sound from wind parks that have floating and sea-floor-mounted foundations. The Belgian part of the North Sea features bottom-mounted wind mill foundations. During the year 2023, a measuring station was installed within an operational wind park and continuously measured sound pressure levels. Every 8 to 10 weeks, the instrument was serviced. Wind and rotation data were also obtained. Data gathered within the wind park showed an increase in the sound pressure level of up to 20 dB re 1 µPa at maximum rotation speed compared to the period prior to construction, for a wind park built on a 5 m-diameter steel monopile equipped with a 3 MW wind turbine. Other data gathered for 2 months inside a neighbouring wind park built on an 8 m-diameter steel monopile equipped with 9,5 MW wind turbine showed a lower underwater sound level elevation.

Keywords

Underwater sound, offshore operational windfarms, sound pressure levels

STUDY B – IMPACTS OF OPERATIONAL OFFSHORE WINDFARMS ON HARBOUR PORPOISE PRESENCE AND FORAGING BEHAVIOUR

Abstract

The North Sea is a crucial habitat for harbour porpoises, which reside year-round in the region. At the same time, the area is undergoing rapid expansion of offshore wind energy, with projections reaching 450 GW by 2050, making it one of the dominant anthropogenic activities alongside fisheries. Understanding how operational offshore wind farms affect marine top predators is therefore essential. Harbour porpoises are particularly sensitive to acoustic disturbance due to their reliance on high-frequency echolocation for navigation, communication and foraging. While the impacts of construction noise are well documented, the effects of operational wind farms remain poorly understood.

This study investigates how operational offshore wind farms and turbine presence influence the foraging behaviour and presence of harbour porpoises at a fine spatial scale. Passive acoustic data were collected over one year using eight bottom-moored cetacean loggers (F-PODs), deployed in the Belgian Part of the North Sea along a distance gradient from 150 to 800 m from the nearest turbine. Presence (Detection Positive Hours, DPH) and foraging (Buzz Positive Hours, BPH) were modelled using Generalized Additive Models in relation to distance to the closest turbine and rotor speed as proxies for operational turbine noise along with several environmental variables.

Harbour porpoise presence showed a clear spatial pattern, with higher occurrence closer to turbines, indicating no evidence of avoidance and suggesting potential attraction or favorable conditions near turbine structures. A significant interaction between rotor speed and distance indicated that turbine-related effects were localized, with a slight decrease in presence at higher rotor speeds close to turbines. In contrast, foraging behaviour showed no significant relationship with distance to turbines and was primarily driven by environmental and temporal factors such as sea surface temperature, chlorophyll concentration, and diel phase. Rotor speed had only a small negative effect on foraging probability.

Overall, these findings suggest that operational offshore wind farms do not lead to large-scale displacement of harbour porpoises but instead result in subtle, context-dependent behavioral responses. The increased presence near turbines may reflect indirect ecological effects such as enhanced prey availability, while foraging behaviour appears to be governed mainly by environmental conditions.

This research was conducted within the framework of PURE WIND, a UN Ocean Decade endorsed project that investigates broader ecological impacts of operational offshore wind farms on the marine food web, from top predators like seals and harbour porpoises to zooplankton.

Keywords

Harbour porpoise, *Phocoena phocoena*, foraging, presence, operational offshore wind farms, modelling, operational noise,

1. INTRODUCTION

STUDY A

The Belgian continental plate is a relatively small maritime domain that encompasses numerous anthropogenic activities, including energy production.

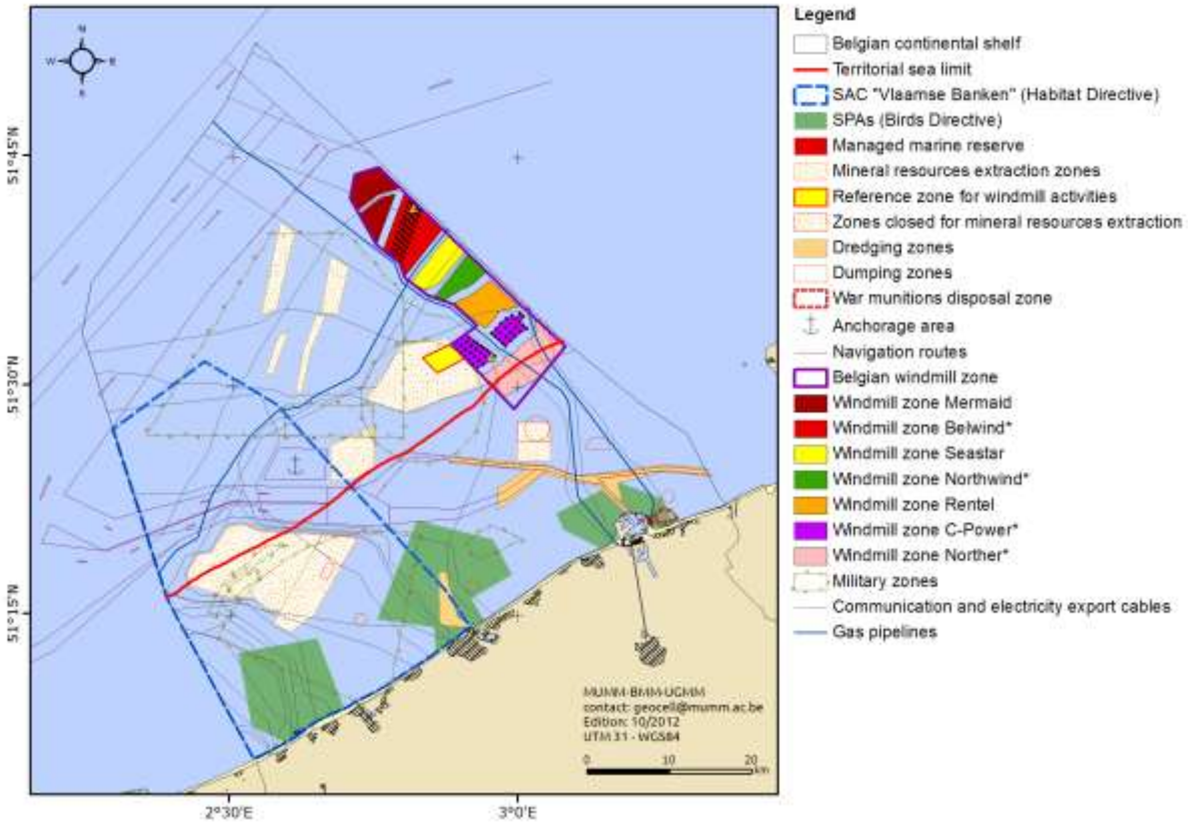


Fig. 1 Belgian zone of energy production zone next to the border with The Netherlands

Within the Belgian zone, 399 wind turbines have been installed across nine parks, representing an installed power of 2,26 GW (Fig.1). They have been operational in sequence since 2010, with the first park. Production is expected to be 8TWh/y. Wind turbines are primarily installed on steel monopiles; 345 installations feature a steel monopile with a diameter ranging from 5 to 8,5 m. Forty-eight jacket-style foundations have been used within a single park, together with six gravity-based foundation fig.2

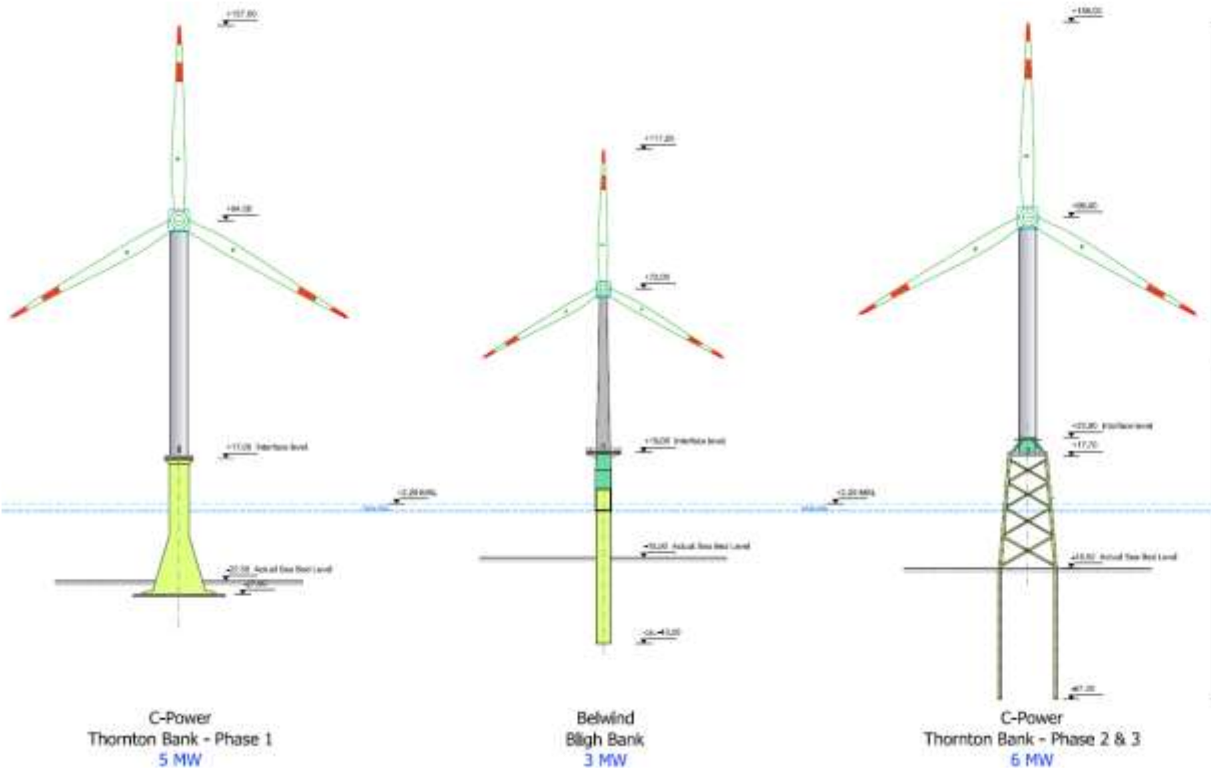


Fig. 2: The three foundation types used in the Belgian North Sea zone. Steel monopile (middle) has a wind turbine ranging from 3 to 9,5 MW

Measurements of operational sound in various offshore wind farms showed a higher sound intensity than the background sound intensity (Andersson et al., 2011; Boesen & Kjaer, 2004). A 6 MW monopile-based wind turbine, for example, is audible at distances of at least 20 km (Marmo et al., 2013). In a more focused report, Betke (2006) documented the sound emitted by a 2 MW turbine using spectral analysis. The highest sound pressure levels are observed near 150 Hz and 300 Hz, at 118 dB and 105 dB re 1 µPa, respectively. No increase in sound pressure level above the background level was observed for frequencies above 800 Hz. A comparison with data measured in Sweden (the Utgrunden wind farm, cited by Betke, 2006) showed a similar pattern. Uffe (2002) further demonstrated that concrete and steel pile foundations exhibit distinct spectral features, and that the sound emitted by both types of foundation is stronger than the ambient sound only at frequencies below 1kHz (steel pile foundations being noisier) (Nedwell et al., 2007). More recently, Stöber & Thompen (2021) proposed a source level for a single wind turbine of 177 dB re 1 µPa m. (gearbox type) with a possible reduction by 10dB if the gearbox is replaced by a direct drive design. Tougaard et al. (2020) concluded that underwater sound radiated by a single wind turbine remains lower than that of a large cargo ship; however, of course, the same authors modelled that the cumulative effect of a single wind farm approaches that of a large cargo ship. They concluded that, as the surface area occupied by wind farms increases and will continue to do so in the North Sea, this underwater sound source cannot be ignored. Belmann et al. (2024) complete this analysis, highlighting that the sound is radiated mainly at low frequencies (below a few hundred Hz) and locally.

Two approaches are available for assessing the underwater sound radiated by the wind park's operation.
The first identifies all new anthropogenic sound sources individually and then sums them. This mainly considers separately additional shipping due to service operations, such as Crew Transfer vessel (CTV) or dynamic positioning (DP) of some survey or working platforms based on the AIS system, and sound radiated by wind turbines.

We consider here the operation of a wind park as a unique process and are not interested in distinguishing among all underwater sound sources associated with power production.

Belwind is a wind park with an installed capacity of 165 MW, comprising 55 Vestas V112-3 MW turbines on 5 m-diameter steel monopiles and has been operating since 2011. Northwester II is a park with 219 MW installed power, comprising 23 Vestas V164 turbines of 9,5 MW installed on 8,5 m-diameter steel monopiles. NWII has been operational since 2021.

STUDY B

The harbour porpoise, *Phocoena phocoena*, is a small, highly mobile cetacean widely distributed across European coastal and offshore waters (Hammond et al., 2002, 2013; Reid et al., 2003). Over the past decade, their distribution in the North Sea has shifted southwards, making the southern North Sea, including Belgian waters, one of their most important habitats (Haelters et al., 2011; Hammond et al., 2013; Nachtsheim et al., 2021). As top predators, harbour porpoises play a crucial role in marine ecosystem dynamics and serve as indicators of ecosystem health. Their year-round presence in these waters, combined with a reliance on high-frequency echolocation for navigation, communication and prey detection, makes them particularly sensitive to anthropogenic disturbance (Booth, 2020; Dracott et al., 2025; Leopold et al., 2015).

The Belgian part of the North Sea (BPNS) is a heavily industrialized marine area, supporting intensive shipping, sand and gravel extraction, dredging, fisheries, aquaculture, and, increasingly, offshore wind energy development (Brabant et al., n.d.; Emeis et al., 2015; Kaiser et al., 2002; Moullec et al., 2021). Offshore wind energy represents the fastest-growing marine industrial activity in Europe, with projections of up to 450 GW installed in the North Sea by 2050 ('Offshore Wind Energy', n.d.). As a result, wind farms now create one of the largest continuous physical and acoustic footprints in the region with a zone of 523 km^2 reserved for offshore wind in the BPNS (Degraer et al., 2023; Norro et al., 2011; Tougaard et al., 2020). Understanding how harbour porpoises interact with this type of infrastructure is critical for conservation and management.

Construction-phase impacts of offshore wind farms, particularly pile-driving noise, are relatively well understood, with documented displacement and stress responses in marine mammals (Benhemma-Le Gall et al., 2021; M. J. Brandt et al., 2011; Dähne et al., 2013; Norro et al., 2010; Schaffeld et al., 2020; Tougaard, Carstensen, et al., 2009). In contrast, the operational phase remains poorly studied. Operational turbines generate continuous low-frequency noise, and their structures may act as artificial reefs, altering local prey availability (Clausen et al., 2021; Fernandez-Betelu et al., 2022; Glarou et al., 2020; Scheidat et al., 2011; Vallejo et al., 2017). These factors could lead to behavioral changes in harbour porpoises, yet empirical data on fine-scale responses and specifically foraging behaviour remain scarce.

For harbour porpoises, foraging behaviour is particularly informative. As echolocating predators, they rely on high-frequency sound to detect prey, and disturbances that interfere with acoustic perception can affect foraging efficiency and habitat use (Booth, 2020; Kastelein et al., 2018; Miller, 2008; Verboom, 1997; Verboom & Kastelein, 2003; Wisniewska et al., 2016). Examining fine-scale foraging behaviour provides insight into habitat quality and can reveal subtle responses to anthropogenic activities such as operational offshore wind farms (OWFs).

2. MOTIVATION AND OBJECTIVES OF THE PROJECT

STUDY A

Studies conducted in Belgian waters (Norro et al., 2011; Norro & Degraer, 2016)have shown an increase in underwater sound levels inside the wind park.
In this report, a description and analysis of newly acquired data from the JPOcean PUREWIND project at the Wind Park BELWIND and Northwester II. The complete dataset will be analysed and further uploaded to the OSPAR database of continuous sound using the JOMOPANS format (Merchant et al., 2018). This data treatment produces monthly percentiles of the SPL distribution, based on individual 1-s SPL measurements.

STUDY B

Studies on how harbour porpoises respond to operational turbine noise are limited, particularly at close distances (<1 km). It is unclear whether porpoises avoid turbine areas due to noise (Tougaard et al., 2020; Tougaard, Henriksen, et al., 2009), are attracted by enhanced prey availability near turbine foundations (Clausen et al., 2021; Fernandez-Betelu et al., 2022; Glarou et al., 2020), or both. Few studies have combined year-round passive acoustic monitoring with continuous environmental and turbine-operation data to assess these behavioral patterns at fine spatial and temporal scales.

This study aims to address these gaps by investigating how operational offshore wind turbines influence harbour porpoise presence and foraging behaviour in the BPNS. Using year-round passive acoustic monitoring with FPODs in combination with a gradient design spanning 150–800 m from turbines, the study examines how porpoise activity relates to turbine rotor speed and distance as a proxy for operational noise, alongside a range of environmental and temporal covariates.

Developed as part of the PURE WIND UN Ocean Decade project, this work links fine-scale behaviour to turbine operation and provides insights directly relevant to conservation and management within European frameworks, including the Habitats Directive and ASCOBANS. The findings further advance understanding of the ecological implications of offshore wind expansion and inform sustainable marine spatial planning. As part of Work Package 3 Noise impacts from offshore wind energy generation across the marine food web, these results fulfil Deliverable 3.3 Determination of harbour porpoise activities in operational OWF, Milestone 3.3 Dedicated PAM-setup deployed at operational OWF, and the harbour porpoise part of Deliverable 3.6 Assessment of impacts of OWF on top predators.

3. METHODOLOGY

STUDY A

For the purpose of the project PUREWIND, in 2023 and every 8 to 10 weeks thereafter (table 1), a measuring station composed of a sound recorder attached to a modified version of a small tripod (Goossens et al., 2020), equipped with an acoustic-operated float for recovery, was deployed within the Belwind wind park and the Northwester II park situated on its west side (see Fig. 3). The hydrophone is detached from the body of the hydrophone (Robinson et al., 2014) and the hydrophone is further attached to the mooring line or structure using a in-house specific suspension setup. Photo 1.

Photo 1: Hydrophone suspension design developed and used at RBINS

The deployment and recovery were operated from the Research Vessels Belgica or Simon Stevin, at deployment, it was lowered to the seafloor using a remotely controlled carabiner operated from the surface, in addition when deployment was made from RV Belgica an additional HYPAP USBL transducer was positioned just above the tripod on the deployment cable to register the exact position of the mooring (Fig.4). The recovery involved the acoustic triggering of a VEMCO AR (operated from a RHIB), which released a float that brought an 8mm Dyneema rope to the surface to recover the complete system. This SOP (Standard Operating Protocol) helps prevent damage to sensitive underwater noise-recording equipment. Fig. 4. To avoid any perturbations both in the sound records and for the CTV operating inside the windpark, no surface marker was attached to the mooring.

Two types of recorders have been used. OCEAN-INSTRUMENT Sound trap ST500 equipped with proprietary hydrophone and RTsys SYLENCE-LP equipped with HTI 96-Min hydrophone. A third one concerned the 2016 dataset at C-Power that is shared with the University of Genova. Here, an AURAL M2 recorder was used and mounted on a large tripod structure.
Both recorders were configured for continuous recording at 64kHz for RTsys SYLENCE-LP and at 72kHz for the OCEAN-INSTRUMENT Sound Trap ST500. Before any deployment, pistonphone calibration was made using a B&K Pistonphone type 4229. After recovery, if the recorder was still operational, a second pistonphone calibration was performed. The AURAL dataset was calibrated after the system fully recovered, since a pistonphone was unavailable at the time of the measurement.

Start Date	*Instrument type*	*End Date*	*location*	*Sampling Frequency*
16/6/2016	AURAL M2	24/08/2016	CPOWER 51°23,3 N 2°26,3 E	32k
17/12/2022	ST500	20/02/2023	belwind C3-D3_D4-C4	72k
15/02/2023	SYL	27/04/2023	belwind C3-D3_D4-C4	64k
27/04/2023	ST500	14/07/2023	belwind C3-D3_D4-C4	72k
14/07/2023	SYL	23/10/2023	belwind C3-D3_D4-C4	64k
21/10/2023	ST500	18/01/2024	belwind C3-D3_D4-C4	72k
24/08/2023	SYL	21/11/2023	NW2 B1-C1	64k

Table 1: Available PUREWIND data set (Continuous recording)

Table 1. Presents the available dataset recorded at the Belwind and Northwester II central location (Fig 3) for the complete year 2023, including a few days of 2022 and a few days of 2024.
We note that the recordings at NorthWester II started at the end of the summer till end of November

Metadata were obtained from the hydrographic service of the Belgian coast (MDK Oostende) for the wind at 10m at the station WESTHINDER located near the wind energy zone. The rotation of the wind turbines located all around the recorder (first neighbourhood) was provided by Parkwind, the concessionaire of both Northwester II and Belwind parks. See Fig.5.

Data processing involved custom MATLAB scripts to extract various metrics and spectral analysis. Based on the methodology developed by Norro and Degrear (2016), 20-min records were extracted from the newly available time series. In addition, to avoid flow noise, the extraction was made from the minimum-current windows occurring 2 hours before and 4 hours after the high tide in Zeebrugge. This approach was not automated, unlike that of Van Geel et al. (2020) which could exclude up to 90% of the data for some locations.

Moorings services were offered after 8 weeks when ship time was available, and the impact of hydrophone biofouling on record quality could not always be guaranteed. Therefore, the 20-min records are always extracted during the first 30 days after deployment.
Frequency analysis is also presented using the sound pressure level SPL Decidecade spectral analysis.

For this report, more focus is on the portion of our dataset shared with the Hopavågen lagoon experiment team. Courboulès et al. (2025)and Rousseau et al. (2025) played the recordings underwater during their experiments.

The dataset was collected from 15 December 2023 to 15 January 2024 inside Belwind at the central location between 4 operating wind turbines, BBC3-BBC4-BBD3-BBD4, see Fig.3.

For modelling purposes, another dataset of 3 months of continuously recorded sound, collected at the 51°23,3 N 2°26,3 E C-Power wind park located within the same energy production zone and a few NM south-east of Belwind. The dataset has been shared with the project partner, the University of Genova, which is responsible for modelling. The CPOWER wind park is built on jacket foundations and houses a 6.5 MW wind turbine.

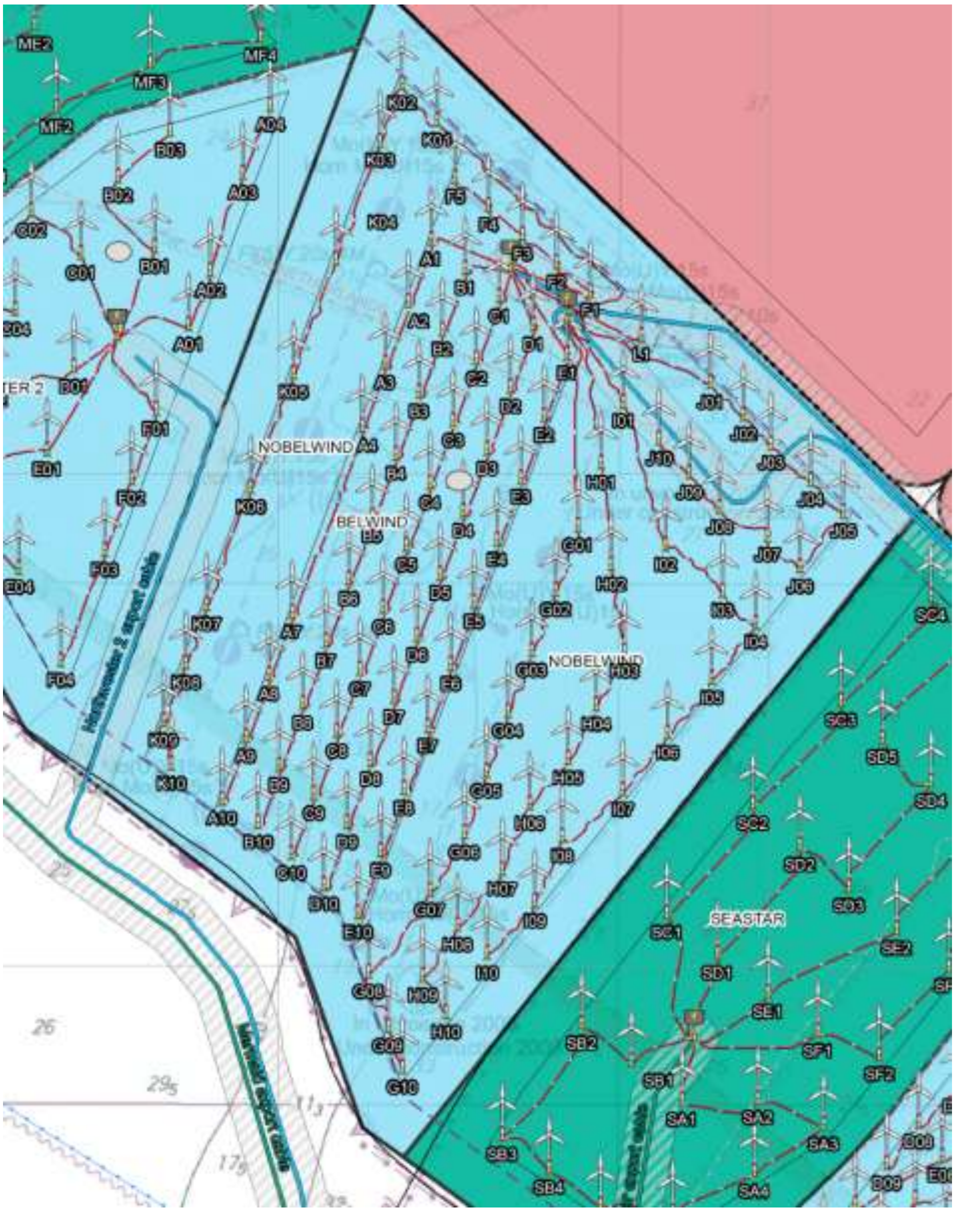


Fig. 3: Mooring position inside the Belwind wind park at the centre of the square C3-D3-C4-D4 (Figure from OTARY) and the NWII location between C01 and B01

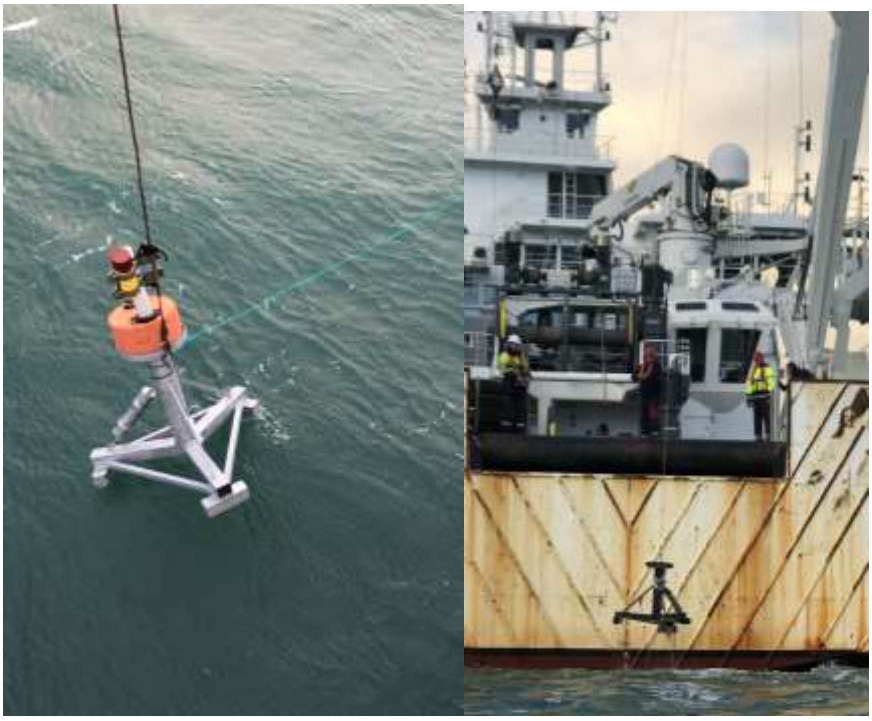


Fig. 4: Mooring operation(left) and recovery (right) from R/V Belgica inside the Belwind windpark.
In this illustration, an RTsys SYLENCE-LP recorder is deployed concurrently with a C-POD attached to the float.

STUDY B

3.1. Study site and set-up

Eight operational OWFs are situated in the BPNS, covering an area of 238 km^2 dedicated to the production of renewable green energy, with a total capacity of 2261 MW (*Belgian Offshore Wind Energy* | *FPS Economy*, n.d.). For this study, the adjacent Belwind and Nobelwind wind farms, comprising 56 and 50 monopiles respectively with a cumulative capacity of 336 MW, have been selected as the sites for deploying acoustic recorders. This choice was made based on the longevity of its operational existence, dating back to 2010, coupled with the fact that the majority of the windfarms constructed have monopile foundations which were found to be the turbine foundations producing the most noise (Norro & Degraer, 2016).
Eight tripods (Calonge et al., 2024) were deployed within the Belwind/Nobelwind OWF following a gradient design. At each of four distance classes (150 m, 400 m, 600 m, and 800 m from the nearest turbine), two replicate tripods were deployed simultaneously, resulting in a total of eight tripods per deployment period.
Distances were defined relative to the closest turbine rather than a fixed turbine, ensuring that measurements reflect general proximity effects and avoid confounding influences of individual turbines.

Deployments were carried out over a 12-month period through successive sampling campaigns. Every three to four months, all tripods were retrieved and redeployed at newly selected, randomized locations within the wind farm. The only exceptions were the 600 m and 800 m distance points, which could not be randomized due to a lack of suitable locations within the wind farm safety zone that met these distance requirements. Despite this constraint, the same distance classes and number of replicates per distance were maintained. This approach ensured consistent sampling effort over time while increasing spatial coverage. Each tripod was equipped with an F-POD (passive acoustic monitoring device), and an acoustic release system as described in Calonge et al, (2024).

A total of 32 tripod deployments were planned, of which 28 were successfully deployed and 26 successfully retrieved (Figure 1). Four deployments could not be carried out due to bad weather, one F-POD was lost upon retrieval, and one deployment is still pending retrieval. To illustrate the temporal and spatial coverage of the F-POD deployments, Figure 2 shows an overview of all deployments, with each row representing a unique pod (UniqueN) and colors indicating the distance to the nearest turbine. Gaps in the plot correspond to periods with no data, either because a deployment did not occur or due to failed retrievals. This visualization confirms that the deployed F-PODs cover the intended range of distances and provides context for the temporal distribution of the acoustic monitoring.

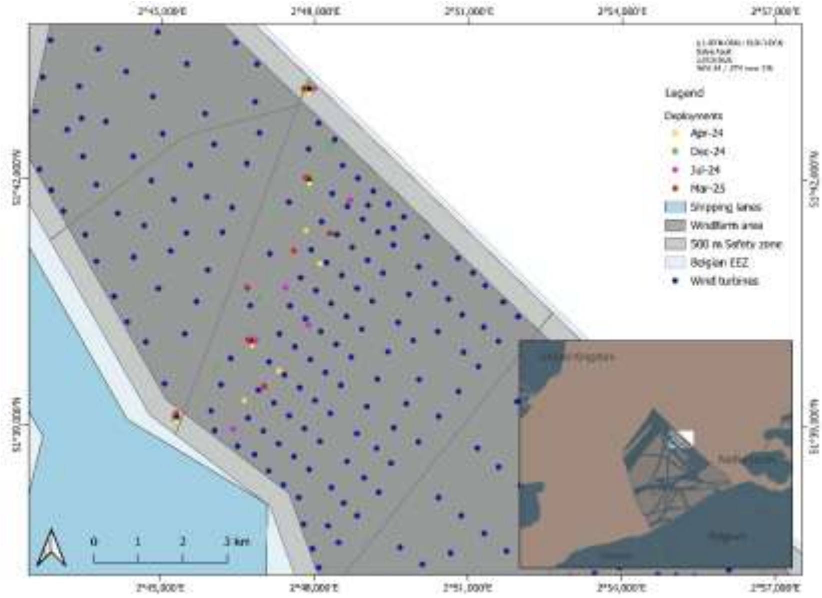


Figure 1 Locations of tripod deployments within the Belwind/Nobelwind OWF and 500 m safety zone. Points are color-coded by deployment period. In each period, up to eight tripods were deployed across four distance classes, with locations re-randomized between deployments where possible.

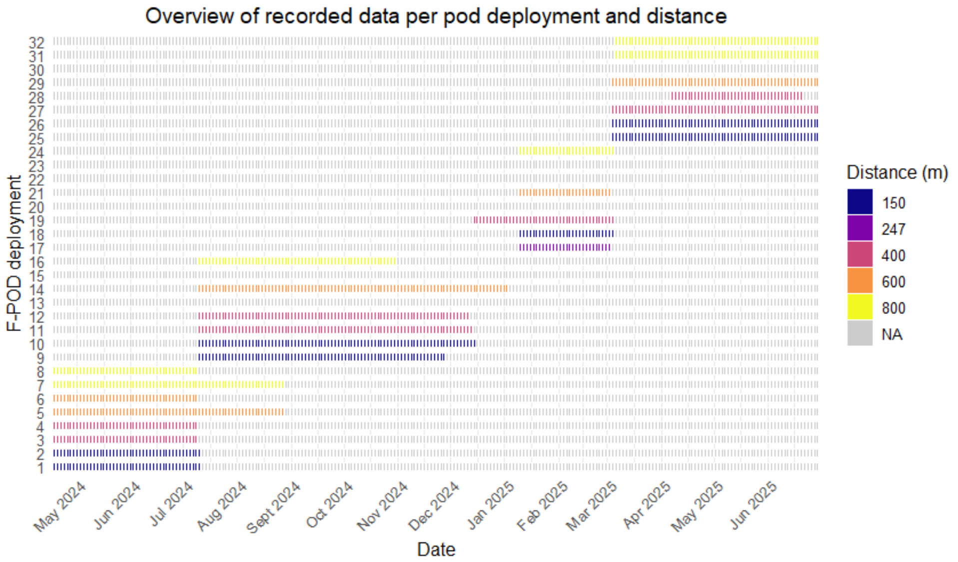


Figure 2 Overview of recorded data per F-POD deployment and distance over the study period. Each horizontal row represents an individual F-POD deployment (UniqueN) and colors indicate the distance of each F-POD to the nearest turbine, a vertical line indicates a day.

3.2. Data analysis

3.2.1. Data processing

The study makes use of passive echolocation-click logging devices also known as F-PODs, that record clicks and click-characteristics for a maximum duration of around 200 days (Chelonia Limited, 2025) with the aim of identifying the foraging behaviour and presence of harbour porpoises around the impacted areas.

The F-POD data were processed using the F-POD.exe software (Version 25 Jan 2024). Detection positive minutes (DPM) and Inter-click intervals (ICIs) for the whole detection period for Narrow-Band High-Frequencies (NBHF) species in High and Moderate quality have been exported using the Chelonia F-POD application on the raw FP3 data to obtain txt files data on detection and behaviour of harbour porpoises for further analysis.

3.2.2. Identifying foraging positive minutes

Foraging-positive minutes were identified using an adapted method, here referred to as the Search Buzz Foraging Identification (SBFI) method, which builds on previous approaches and knowledge (DeRuiter et al., 2009; Miller, 2008; Pirotta et al., 2014; Sørensen et al., 2018). These studies identified foraging buzzes as having an average buzz ICI around 3-3.5 ms and buzz click rates typically ranging from several hundred up to 700 clicks/s (Akamatsu et al., 2007; DeRuiter et al., 2009; Miller, 2008; Verboom & Kastelein, 2003; Verfuß et al., 2009). While social calls are distinguishable from foraging buzzes by their repetition rate and duration, foraging buzz ICI remains relatively constant across different feeding conditions (Sørensen et al., 2018).

The SBFI method emphasizes individual click detections rather than click trains, accounting for the directionality of the echolocation clicks of harbour porpoises which can lead to incomplete or interrupted trains (Berges et al., 2019). Based on these insights and the enhanced sensitivity of F-POD devices compared to C-PODs (Ransijn et al., 2024; N. R. E. Todd et al., 2023), the SBFI method defines a foraging buzz as having at least three consecutive ICIs between 1.25 ms (≈800 clicks/s) and 6.65 ms (≈150 clicks/s). A minute is classified as foraging-positive if a preceding search or approach-phase click is detected, defined as having a click rate below 200 clicks/s, to avoid counting repeated bowl-shaped buzzes as multiple foraging events, while it could indicate social behaviour (Migneault et al., 2025; Miller, 2008).

In cases where multiple buzz sequences occurred within the same minute, each sequence was evaluated independently, and the minute was classified as foraging-positive if any sequence met both criteria. It should be noted that a foraging buzz reflects a foraging attempt rather than a confirmed prey capture.

3.2.3. Variables

Several environmental, operational, and temporal variables were downloaded to investigate potential drivers of harbour porpoise presence and behaviour (Table 1). These variables were selected based on their ecological relevance to prey distribution, habitat suitability, and potential disturbance effects within offshore wind farms.

Spatial variables included distance to the nearest turbine (NearestDistanceMeters), calculated for each F-POD deployment, and bathymetric depth, extracted from EMODnet bathymetry data. Distance was included to assess potential effects of turbine-related noise assuming that the closer to a turbine the louder the underwater noise (Norro et al., 2011; Norro & Degraer, 2016; Tougaard et al., 2020), while depth was considered as a proxy for habitat characteristics, although limited variability was expected due to the constrained study area.

Operational turbine activity within the wind farm was represented by rotor speed (m/s) and was obtained from the wind farm operator for each closest turbine and used as well as a proxy for turbine-generated underwater noise.

Sunrise, sunset, night and night end were obtained for each location and time using the *suncalc* R package (Thieurmel, Benoit & Elmahraoui, Achraf, 2022). Diel phase day was defined as the period between sunrise and sunset, morning was defined as the period between night end (dawn) and sunrise, evening was defined as the period between sunset and night (dusk) and the period between astronomical dusk and dawn or night and night end is categorised as night. This variable was included due to its proven relevance to both harbour porpoise presence as foraging behaviour . Lunar fraction, fraction of the moon illuminated ranging from 0 to 1 was also calculated using the *suncalc* R package (Thieurmel, Benoit & Elmahraoui, Achraf, 2022).

Environmental conditions were characterized using sea surface salinity (SSS), chlorophyll-a concentration (CHL), sea surface height (SSH), and current velocity, obtained from Copernicus Marine Service products. These variables were included as proxies for prey availability and distribution (Bouveroux et al., 2020; IJsseldijk et al., 2015; van Beest et al., 2018; Wingfield et al., 2017; Zein et al., 2019). Current velocity components were further used to derive current speed and direction. In addition, temperature recorded directly by the F-POD devices was included to capture local environmental variability at the deployment sites.
All covariates were matched to the temporal resolution of the acoustic data prior to analysis.

Table 1 Overview of environmental and anthropogenic impact variables that were identified, evaluated and parametrized. For each variable a unit and the resolution is provided, if applicable, as well as a description and the reason for inclusion.

Covariate	**Unit**	**Resolution**	**Description**	**Rationale**	**Data source / calculation**
Distance to the closest turbine	m	1 m	Shortest distance from the FPOD to the closest turbine	To assess the potential effect of sound on presence and behaviour	Calculated with R package "geosphere" (Hijmans et al., 2024).
Depth	m	0.001 m	Bathymetric depth	Relevance to habitat suitability of harbour porpoises for foraging and/or prey – due to location of PODs unlikely to be of great importance	Extracted from harmonised European Marine Observation and Data Network (EMODnet) EMODnet Digital Bathymetry (DTM 2022). EMODnet Bathymetry Consortium https://doi.org/10.12770/ff3aff8a-cff1-44a3-a2c8-1910bf109f85
Temperature	°C	-	Temperature recorded during deployment by the FPOD device	Potential predictor for seasonal patterns or prey patterns	FPOD device
SSS	so [/103]	0.027°	Sea surface salinity for each hour and day	Proxy for porpoise prey distribution (van Beest et al., 2018)	extracted from Met Office NW Shelf models: http://marine.copernicus.eu ; https://doi.org/10.48670/moi-00054

CHL	mg/m3	1kmx1km	Chlorophyll for each day	Possibly a proxy for prey (Wingfield et al., 2017)	extracted from North Sea models: http://marine.copernicus.eu ; https://doi.org/10.48670/moi-00289
Current velocity	m/s	0.027°	Eastward and northward current velocity for each hour and day	Proxy for prey distribution and potentially influencing harbour porpoise behaviour (IJsseldijk et al., 2015)	extracted from Met Office NW Shelf models: http://marine.copernicus.eu ; https://doi.org/10.48670/moi-00054
Rotor speed	m/s	-	Rotor speed from the closest turbine for each FPOD deployment	Proxy for the sound produced by the turbines	Obtained from offshore wind park operator
Tides / Sea surface height	Cm / m	1 cm / 0.027°	Tides TAW – taken from measuring point at Zeebrugge Leopold II dam / sea surface height above Geoid	Relevance to porpoise presence and abundance (Zein et al., 2019)	Extracted from Meetnet Vlaamse Banken / extracted from Met Office NW Shelf models: http://marine.copernicus.eu ; https://doi.org/10.48670/moi-00054
Lunar fraction	-	0.00-1	Illuminated fraction of the moon	Illumination might impact prey presence and foraging behaviour of porpoises	Calculated with R package suncalc (Thieurmel B, Elmarhraoui A 2022)
Dielphase	-	-	Morning, day, evening and night categories	Dielphase has been shown to influence porpoise presence and behaviour	Calculated with R package suncalc (Thieurmel B, Elmarhraoui A 2022)

3.3. Statistical modelling

All statistical analyses were performed in Rstudio (Posit team, 2023) and R version 4.3.1. (R Core Team, 2023). Tables were made using the *gt* R package (Iannone et al., 2025).
Two datasets were considered. The presence dataset (DPH) consists of binary detection positive hours values for all hours when a pod was recording (Figure 2) and the foraging dataset (BPH), consisting of binary buzz (foraging)-positive hours values for all hours where a porpoise was present.

Data exploration was performed to assess temporal and spatial structure in the data prior to modelling. Exploratory data analyses included checking for missing values, outliers and potential collinearity and relationships or interactions using Cleveland dotplots, variance inflation factors (GVIF/VIF) and paired correlation coefficient scatterplots and coplots (Zuur et al., 2010). Variables with strong collinearity (r > 0.7 or VIF > 3) were excluded, keeping NearestDistanceMeters and sea surface height over Depth and tide height. Variables with coarser temporal resolution (daily) such as chlorophyll (CHL), sea surface salinity (SSS), and lunar fraction were considered but included only if they improved model performance without introducing high concurvity, leading to the removal of SSS in the foraging model.

Binary foraging observations were visualized over time and across distance bins using faceted plots, and smoothed trends were inspected to identify potential nonlinear relationships.
To investigate the effects of operational offshore windfarms and environmental variables on harbour porpoise presence and foraging behaviour, generalised additive models (GAM) were used. Models were fitted using the *bam* function from R package *mgcv* (Wood, 2017; Wood et al., 2015), which is constructed for large datasets. The response variables were modelled as binomial outcomes with a logit link function. To prevent overfitting without sacrificing model performance, the gamma parameter was set to 1.4, thereby regulating the model's effective degrees of freedom (Wood, 2017). If the smooth term of an included covariate was only 1 effective degree of freedom (edf), the smoothing function was removed and the covariate was added as a linear term (Wood, 2017)

Prior to model fitting, all continuous covariates were standardized to improve interpretability when not included in a smoother. All models accounted for temporal autocorrelation by including a first-order lag term of the response (BPH or DPH). This acknowledges that if a porpoise is present or foraging in hour x, it is more likely to be present or foraging in hour x+1. Hour of day was modeled using a cyclic cubic spline to capture diel patterns. A random intercept for each pod deployment (UniqueN) was included to account for repeated measures and hierarchical structure of the data. Current speed was fitted as a smooth term by current direction to capture potential direction-specific effects. Other predictors included rotor speed, distance to nearest turbine, sea surface temperature (SST), SSH, and diel phase.

The full model configuration for the harbour porpoise presence and foraging are shown below:

DPH ~ NearestDistanceMeters.std + rotorspeed.std + s(hour) + lag_DPH + s(time_index, UniqueN) + s(SSH) + currentdirection + s(currentspeed) + ti(rotorspeed, NearestDistanceMeters) + dielphase + fraction.std

BPH ~ NearestDistanceMeters.std + rotorspeed.std + s(hour) + lag_BPH + s(UniqueN) + s(SST) + s(SSH) + s(currentspeed, by = currentdirection) + dielphase + fraction.std + s(CHL)

Smooth terms and patterns were visualized using R packages ggplot2 and mgcViz (Fasiolo et al., 2020; Wickham, 2016).

3.3.1. model selection and validation

Model selection was guided by ecological relevance, diagnostic checks using the R package DHARMa (Hartig, 2022), and concurvity measures. Concurvity was evaluated for all smooth terms, and variables causing high concurvity were either removed or modified. Smooth terms were fitted using cubic regression splines with carefully chosen knot numbers to balance model complexity and explanatory power using the *gam.check* function from R package *mgcv* (Wood, 2017). Model validation included inspection of residuals, checks for temporal autocorrelation per pod deployment, and assessment of deviance explained along with the other diagnostics checks from DHARMa (Hartig, 2022).

4. SCIENTIFIC RESULTS, DISCUSSION AND RECOMMENDATIONS

STUDY A

Figure 5 presents the rotation speed (Rotation Per Minute) of the four wind turbines surrounding the recording position inside the windpark Belwind. The windmill is running at its maximum rotation speed of 16 rotations per minute (RPM). The maximum speed also corresponds to the maximum number of occurrences observed here for the full year 2023 and accounts for about 40% of the time, and the same pattern is shown for all four turbines

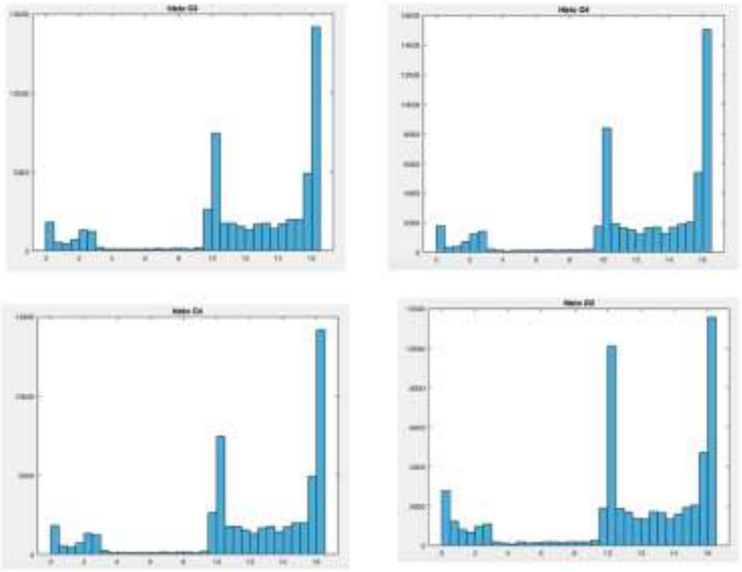


Fig. 5 Histograms of the rotation speed at BBC3, BBC4, BBD3 and BBD4 (Occurrence versus RPM)

Fig. 6 shows, for the dataset under more focus (15/12/23—15/1/24), the maximum over 3 s and the mean wind speed over 10min plotted together with the turbine rotor rotation speed. For a mean wind speed of 11 m/s, the maximum rotation speed of the wind turbine is reached.

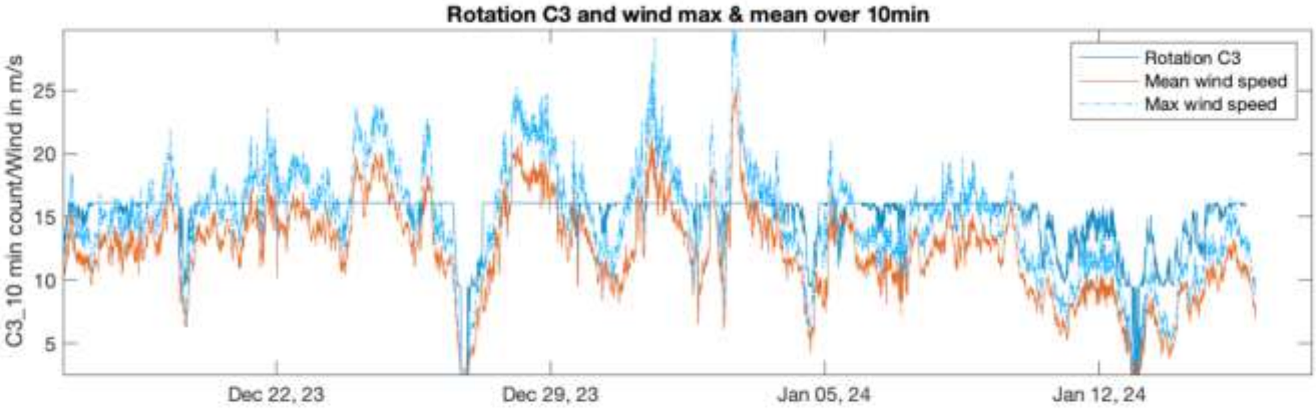


Fig. 6 Maximum & mean wind speed observed at Weshinder (MDK Oostende) with the rotation speed at BBC3

To better focus on the rotation time series for the one-month period of interest (15/12/23-15/1/24), Figure 7 presents rotation for the wind turbine BBD4. For this period of time, the maximal rotation is present for more than 85% of the period. That was precisely the selection criterion for this dataset, as articulated by Justine Courbelès. Fig 9 presents the rotation histograms for the two turbines at B01 and C01, the closest turbines to the moored underwater sound recorder at NorthWester II . When the turbine has a higher capacity, the maximum rotation speed is lower; and for the concerned wind turbine, it is 11 RPM.

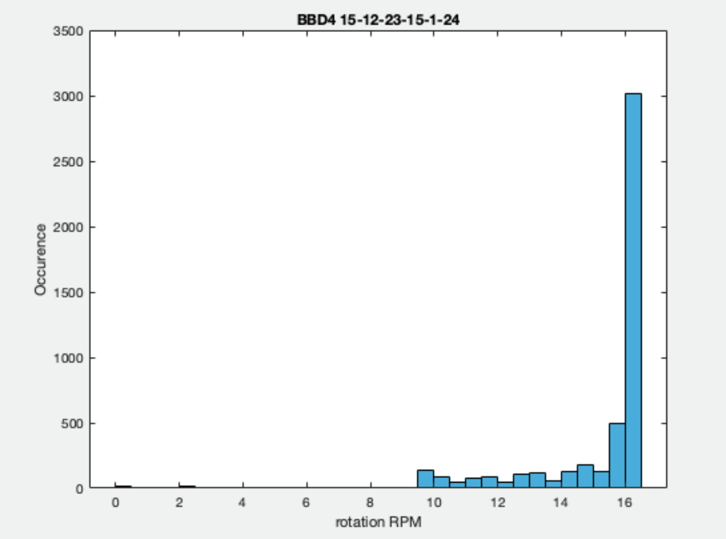


Fig. 7 Histograms of the rotation speed for BBD4 during the period 15 December 2023 to 15 January 2024 (Occurrence versus RPM)

All wind turbines in this wind park are equipped with gearboxes; the rotation of the gearbox's internal components generates vibration, which is further transmitted into the water through the metallic foundation and propagates into the environment. Spectral analysis is presented in Fig. 8, showing our results during a maximal rotation phase in blue and a no rotation period in pink.

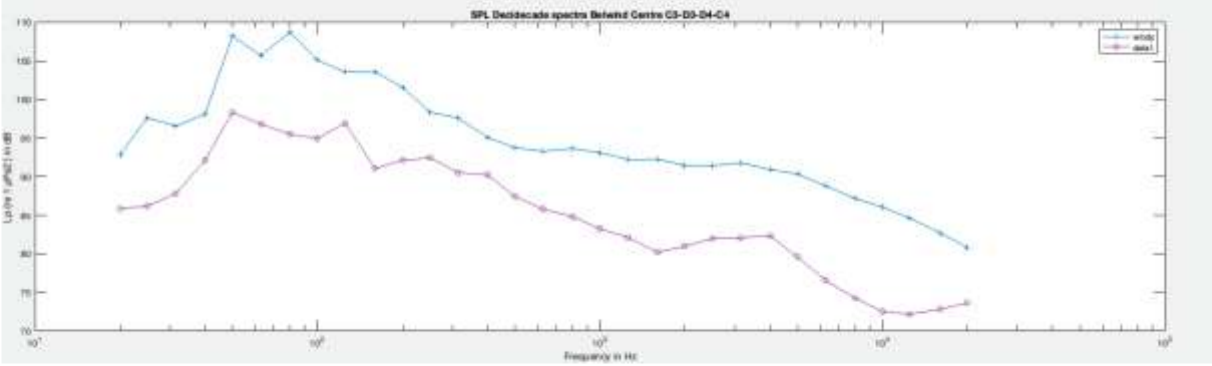


Fig. 8 SPL Decidecade spectral analysis featuring underwater sound measured during a 20min records taken at maximal rotation of 16 RPM (blue) and at no rotation (pink)

An increase of approximately 10-15 dB re 1 µPa of the levels of underwater sound is observed between the conditions at full rotation speed and no rotation at Belwind. This is observed across the entire spectrum, with some peaks below 200 Hz.

The further analysis of those peaks falls outside the scope of this report. An example of such analysis is given in Trucco and Neves (2025). The Genova University (Andrea Trucco's team) conducted further analysis on the shared dataset taken inside the CPOWER wind farm. They examined the turbine-specific tonal signal in the provided raw data and found none. This demonstrates that when the recorder is located far enough from the jacket foundation, and in this situation, that is about 400m, no tonal signal can be observed over the background sound, considering that the background sound of the Belgian zone of the North Sea is high. This further confirms the local effects of operational sound generated by wind parks.

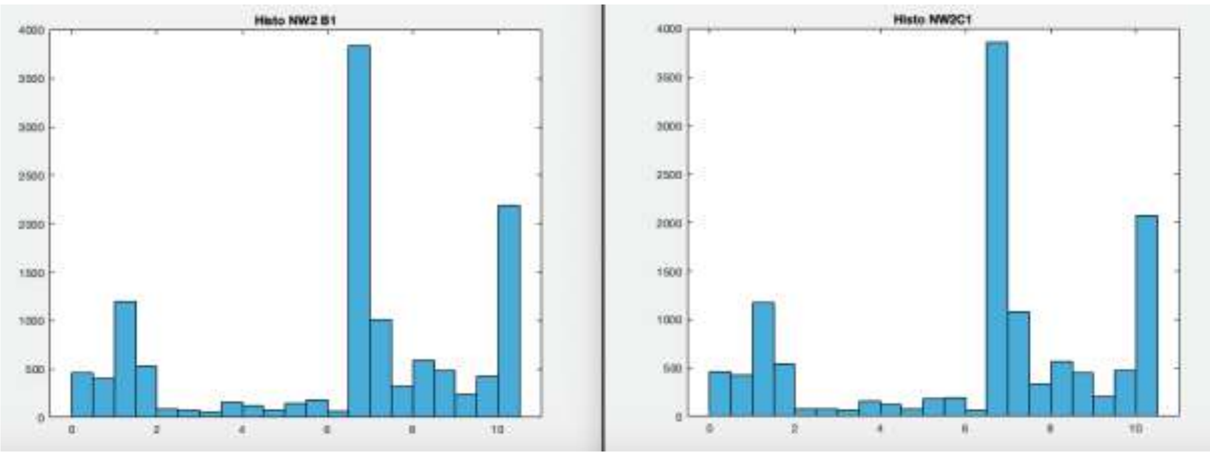


Fig. 9 Histogram of the rotation of the two turbines of the park NW2

Figure 10 presents the results of a similar case, but for a larger monopile, 8 m in diameter, equipped with a 9,5 MW wind turbine. Here, too, we observe a difference in the generated levels of underwater sound between calm conditions with no rotation and windy conditions at the maximal rotation speed of 11 RPM. For this situation, the level differences are smaller, in the range of 10 dB re 1 µPa (Fig. 10) if one smooths the large peaks appearing below 400 Hz in Northwester II (Fig 10).

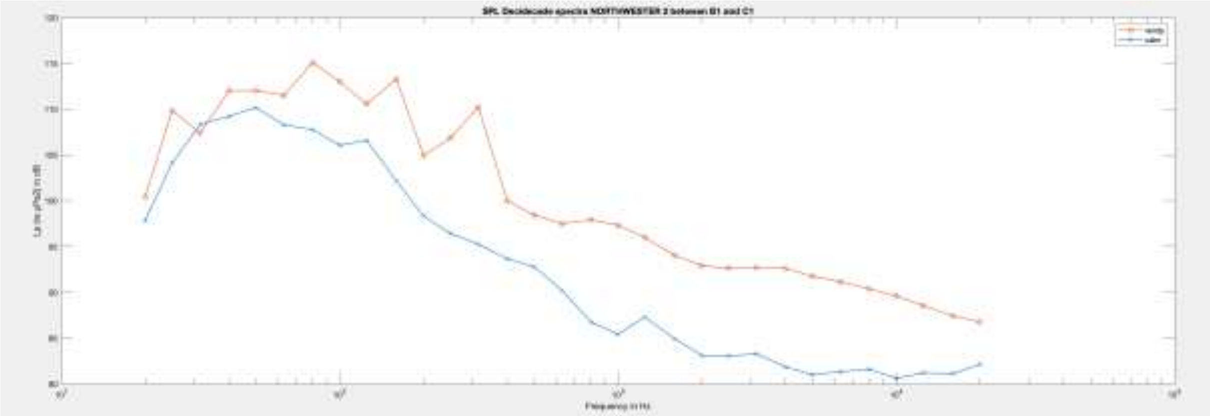


Fig. 10 SPL Decidecade spectral analysis featuring underwater sound measured during a 20min records taken at maximal rotation of 11 RPM (red) and at no rotation (blue)

The main lesson from this spectral analysis is that, at full rotation, the wind park emits higher underwater sound levels than when the turbines are stopped. When compared with background sound measured on site before construction of the windpark, which was a maximum of 100 dB re 1 µPa (Haelters et al., 2009), we can confirm a net increase in SPL of at least 15-20 dB re 1 µPa.

Targeted data treatment has been applied to the dataset obtained by the project. The focus of the PUREWIND project was to identify any modifications in underwater sound that could be associated with the operation of the wind park.

Norro and Degrear (2016) conducted this analysis for the Belwind park and for wind speeds up to 12 m s^{-1}. They extracted a linear relationship between wind speed and the underwater sound emitted by the wind park. The slope of the linear model is statistically significant.
For the additional data provided by this project, the results are similar with a SPL of 129 dB re µ Pa , and 95 percentile at 135 dB re 1µPa is observed at maximal rotation corresponding with a wind of 11 ms^{-1}. We can confirm from our dataset gathered at NorthWester II, that larger wind turbines are not radiating a stronger level of underwater sound, confirming here the conclusion of Belmann et al 2024. We observed a lower level difference between full rotation

and no rotation. We hypothesise that the lowest rotation speed of a new-generation gearbox reduces radiated underwater sound.

The JPIOcean PUREWIND project enabled the collection of a new dataset of underwater sound recorded within the operational wind park BELWIND and NorthWester II. A portion of the dataset was shared within the project and used to play underwater during an experiment on zooplankton ecology. Another data set originating from another Belgian wind park was shared with the University of Genova.

The characterisation of the dataset under focus showed an increase in the radiated underwater sound resulting from the operation of the windpark; no discrimination between sound sources was sought; instead, the operational process was considered as a whole.

Computation of SPL and the 95 SPL percentile, as well as spectral analysis, demonstrated differences up to 15 dB re 1 µPa between the situation at maximal rotation of the wind turbine (wind of 11 ms^{-1}) and the one at no rotation inside the wind parks. Moreover, it was shown that a larger steel monopile equipped with a larger wind turbine, which rotates at a lower speed, radiates at a lower underwater sound level than the smaller one rotating at a higher speed.

The Norro and Degraer 2016 model is confirmed for the Belwind park and could be used to model the cumulative effects of multiple wind farms in the marine zone. This is after Tougaard et al. (2020); the main question to be addressed in the future is how to account for the increasing number of wind farms in the North Sea and other maritime domains, given that wind farms are local sources of radiated underwater sound.

STUDY B

4.1. General patterns and overview

A total of 10 514 hours of data, spanning 439 days, were analyzed in this study. Harbour porpoises were detected during 44.48% of the total hours recorded and at least once every day of the recorded period. Presence showed clear seasonal variation, with the lowest detection rates observed in late summer and early autumn, particularly in August (25.67%) and September (24.33%), and highest detection rates during late winter and spring, peaking in February (69.20%) and April (70.84%) (Table 2; Figure 3).

Foraging behaviour was recorded during 52.16% of the hours in which porpoises were present. Similar to presence, foraging behaviour exhibited strong seasonal patterns, with highest proportions of foraging occurring in spring (April; 69.99%) and winter (December; 58.88%) and the lowest proportions during summer, particularly in June (36.48%) (Table 2; Figure 3).

Table 2 Summary table of presence and foraging hours on total hours (proportion) per month.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Presence	54.03	69.20	60.24	70.84	46.52	33.07	41.57	25.67	24.33	32.18	31.40	63.88
Foraging	54.20	58.88	62.30	69.99	49.73	36.48	40.53	37.53	40.91	45.44	45.65	58.88

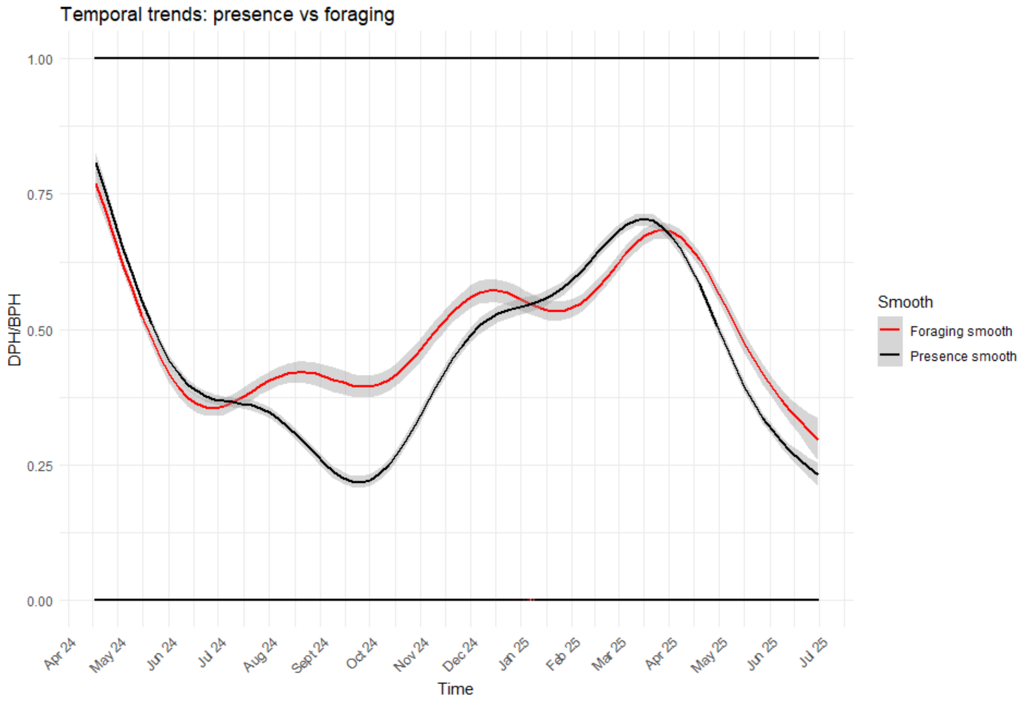


Figure 3 Temporal trend of Detection Positive Hours (DPH - blue) and Buzz Positive Hours (BPH - red) over time with a gam smooth.

Overall, both presence and foraging peaked during winter and spring and declined during summer. However, temporal trends differed slightly. While presence showed a pronounced trough in early autumn (September–October), this decline was less evident for foraging, which exhibited a more gradual increase from late summer into autumn (Figure 3).

While harbour porpoise presence showed clear diel variation, the dominant period differed across seasons. In winter, most detections occurred during the night, whereas in spring detections were more frequent during the day. In contrast, presence was more evenly distributed between day and night during summer and autumn (Figure 4).

Foraging behaviour exhibited a different pattern. In summer and autumn, foraging occurred predominantly during the night, whereas in winter and spring the distribution of foraging between day and night was more balanced (Figure 4).

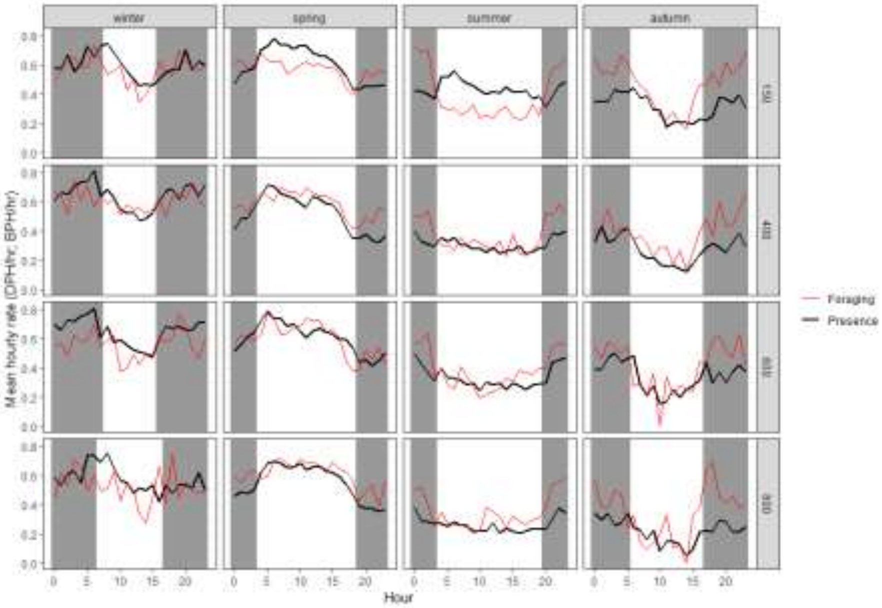


Figure 4 Diel variation in harbour porpoise presence (DPH; black line) and foraging behaviour (BPH; red line) across seasons (columns) and distance classes (rows). Values represent mean hourly rates aggregated per distance and season. Background shading indicates diel phase, with night shown in grey and day in white. Foraging (BPH) reflects the proportion of hours with foraging behaviour conditional on porpoise presence.

4.2 Presence model results

The final model explained 14.9% of the deviance in harbour porpoise presence, with an adjusted R^2 of 0.19, based on 65 584 observations. Overall, the model showed moderate explanatory power, with several environmental and temporal predictors contributing significantly to variation in porpoise occurrence. SST, SSS, and CHL were checked but removed due to added concurvity to the model.

A strong temporal dependence was observed, with the lagged presence term (lag_DPH) being highly significant ($p < 0.001$). This indicates that porpoise presence in a given hour was strongly influenced by presence in the preceding hour, reflecting short-term persistence in habitat use. A significant factor-smooth interaction between time and deployment (s(time_index, UniqueN), $p < 0.001$) was included to account for site-specific temporal trends, allowing the temporal pattern of porpoise presence to vary across individual monitoring stations, since adding UniqueN as a random effect and the lag DPH did not solve temporal autocorrelation fully.

Porpoise presence varied across diel phases, although the effect was relatively modest. Compared to daytime conditions, presence was significantly higher during the evening (estimate = 0.14, $p = 0.002$), while no significant difference was detected during the morning ($p = 0.51$). Night-time presence showed a weak, non-significant increase ($p = 0.086$). In addition, a significant nonlinear effect of hour of day was detected (edf = 5.33, $p < 0.001$), indicating continuous variation in presence throughout the day (Figure 5).

Sea surface height (SSH) had a significant nonlinear effect (edf = 2.92, $p < 0.001$), suggesting that porpoise occurrence decreases after a SSH larger than 1. Similarly, current speed showed a significant nonlinear relationship (edf = 2.87, $p < 0.001$), where occurrence decreased at higher current speeds (Figure 5). Current direction further contributed to variation in presence, with several directions (north, northeast, northwest, southwest, and west) associated with significantly lower probabilities of presence compared to the reference category east, indicating direction-specific hydrodynamic effects. Lunar fraction had a significant positive effect on presence (estimate = 0.07, p < 0.001), indicating a slight increase in detection probability with increasing moon illumination.

Distance to turbine was identified as a significant predictor, with a negative relationship indicating decreasing probability of presence with increasing distance (estimate = −0.44, p = 0.004, Figure 5). Looking at the proportion of hours during which porpoises were present, there were some differences amongst distance classes, ranging from 47.68% at 150 m to 40.98% at 800 m. Rotor speed itself was not a significant predictor (p = 0.28). However, a weak but significant interaction between rotor speed and distance was detected (p = 0.003), suggesting that higher rotor speed has a negative effect at closer distances while at further distance this effect is negligible, similarly low rotor speeds also seem to have a negative effect on intermediate distances although the magnitude of this interaction was small (Figure 5).

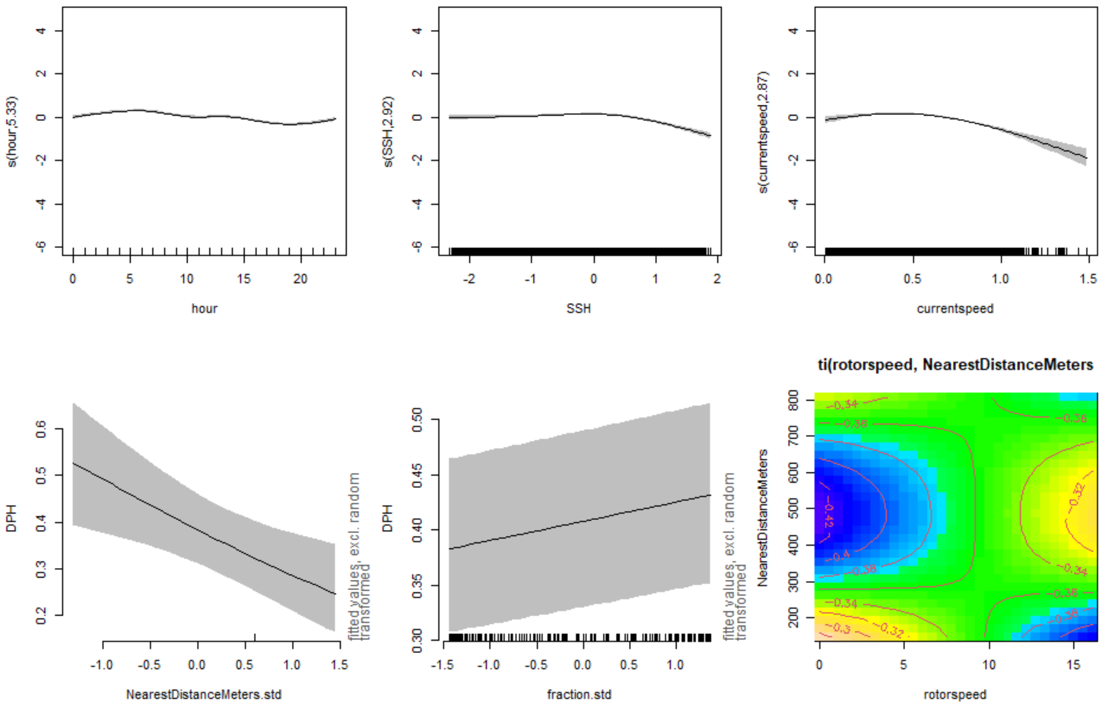
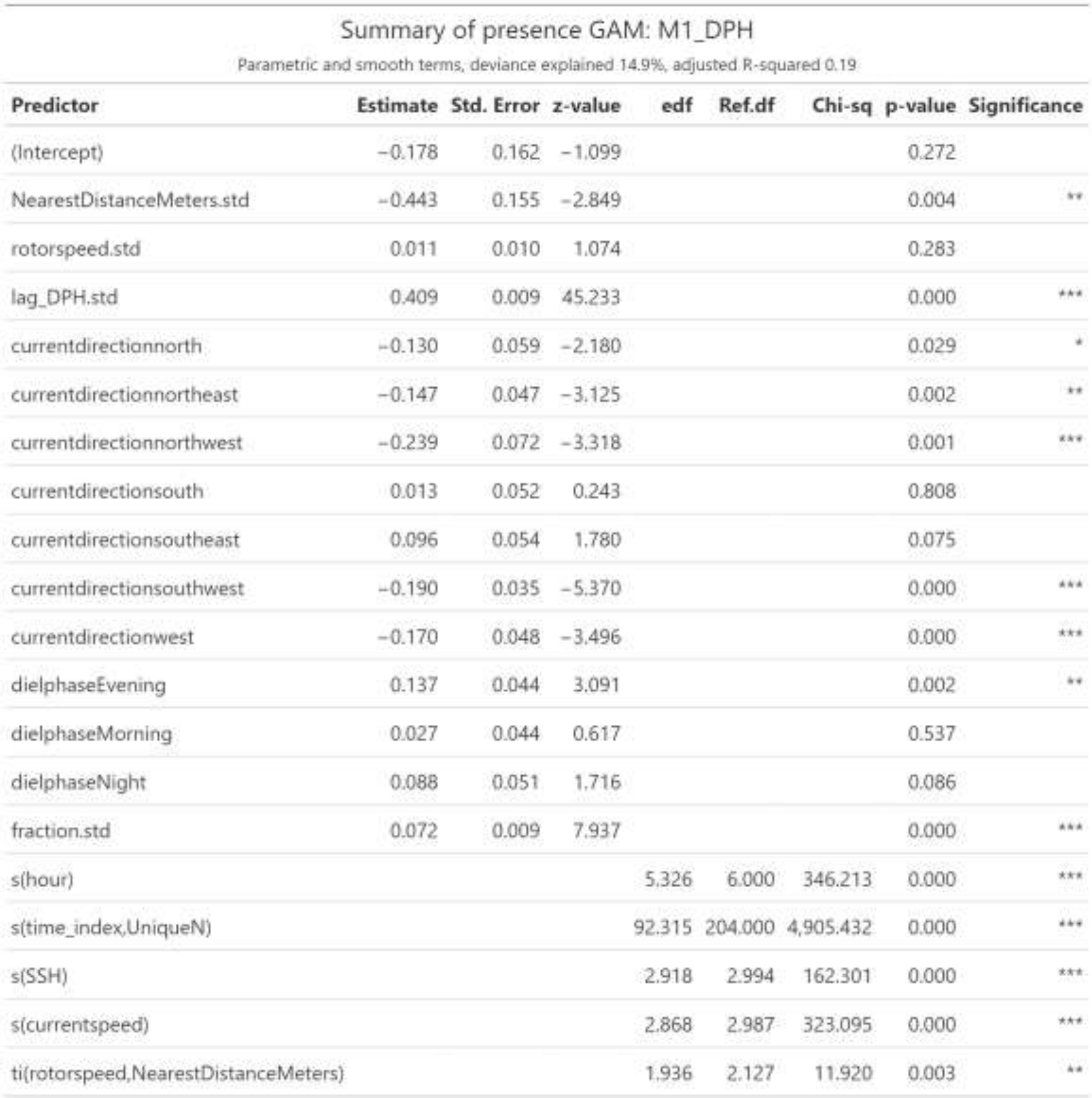


Figure 5 Partial effect plots of explanatory variables, with 95% confidence intervals (grey-shaded areas), selected in the final presence model. X-axis ticks indicate the spread of the data points used to estimate the partial effect plots.

Table 3 Model summary and outputs of the binomial presence model



Summary of presence GAM: M1_DPH

Parametric and smooth terms, deviance explained 14.9%, adjusted R-squared 0.19

Predictor	Estimate	Std. Error	z-value	edf	Ref.df	Chi-sq	p-value	Significance
(Intercept)	−0.178	0.162	−1.099				0.272	
NearestDistanceMeters.std	−0.443	0.155	−2.849				0.004	**
rotorspeed.std	0.011	0.010	1.074				0.283	
lag_DPH.std	0.409	0.009	45.233				0.000	***
currentdirectionnorth	−0.130	0.059	−2.180				0.029	*
currentdirectionnortheast	−0.147	0.047	−3.125				0.002	**
currentdirectionnorthwest	−0.239	0.072	−3.318				0.001	***
currentdirectionsouth	0.013	0.052	0.243				0.808	
currentdirectionsoutheast	0.096	0.054	1.780				0.075	
currentdirectionsouthwest	−0.190	0.035	−5.370				0.000	***
currentdirectionwest	−0.170	0.048	−3.496				0.000	***
dielphaseEvening	0.137	0.044	3.091				0.002	**
dielphaseMorning	0.027	0.044	0.617				0.537	
dielphaseNight	0.088	0.051	1.716				0.086	
fraction.std	0.072	0.009	7.937				0.000	***
s(hour)				5.326	6.000	346.213	0.000	***
s(time_index,UniqueN)				92.315	204.000	4,905.432	0.000	***
s(SSH)				2.918	2.994	162.301	0.000	***
s(currentspeed)				2.868	2.987	323.095	0.000	***
ti(rotorspeed,NearestDistanceMeters)				1.936	2.127	11.920	0.003	**

4.3. Foraging model results

The final model explained 5.89% of the deviance in foraging occurrence, with an adjusted R² of 0.0779 and a total of 29 175 observations. While overall explanatory power was modest, several environmental and temporal predictors were identified as significant contributors to variation in foraging behaviour.

A strong temporal dependence was observed, with the lagged foraging term (lag_BPH) being highly significant ($p < 0.001$). This indicates that foraging behaviour in a given hour was strongly influenced by foraging activity in the preceding hour. Inclusion of this term also improved model diagnostics by reducing temporal autocorrelation.

The probability of foraging varied significantly across diel phases. Compared to the reference category day, the probability of foraging was significantly higher during the morning (estimate = 0.43, $p < 0.001$), evening (estimate = 0.36, $p < 0.001$), and night (estimate = 0.36, $p < 0.001$). These results indicate increased foraging activity outside of daytime conditions. A significant nonlinear effect of hour of day was detected (edf = 4.61, $p < 0.001$), indicating that foraging activity varied throughout the day in a non-uniform manner. The probability of foraging occurrence reached a peak around the morning and decreases throughout the day after which it increases again from 17h onwards (Figure 6).

Sea surface temperature had a strong and significant nonlinear effect on foraging occurrence (edf = 4.82, $p < 0.001$). The probability of foraging occurrence significantly decreased with higher temperatures with most foraging estimated around 8-11 °C coinciding with the sea surface temperatures around winter and spring.

Chlorophyll concentration showed a significant but less complex relationship with foraging activity (edf = 2.72, $p < 0.001$). Foraging probability increased with chlorophyll concentration up to approximately 2.5 mg/m³, after which the relationship plateaued, suggesting a threshold effect in the influence of primary productivity.

The interaction between current speed and direction revealed direction-specific effects on foraging behaviour. Significant relationships were observed for northeast ($p = 0.005$) and southwest ($p < 0.001$) current directions, whereas other directions did not show significant effects. These results indicate that the influence of current speed on foraging is dependent on flow direction, highlighting the importance of local hydrodynamic conditions.

The proportion of hours during which porpoises were detected foraging was similar across distance classes, ranging from 50.3% at 150 m to 53.6% at 800 m. Although a slight increase in foraging activity with distance was observed, the magnitude of this difference was small and does not indicate a strong spatial pattern. Consistent with this, distance to turbine was not identified as a significant predictor in the model. An interaction between rotor speed and nearest distance to the turbine was tested but left out of the model due to no significance and to avoid potentially weaking the rotor speed effect.

Rotor speed had a small but statistically significant negative effect on foraging occurrence (estimate = −0.028, $p = 0.044$), indicating a slight decrease in the probability of foraging with increasing rotor speed. Similarly, lunar fraction also indicated a small but statistically significant positive effect on foraging occurrence (estimate = 0.025, $p = 0.043$).

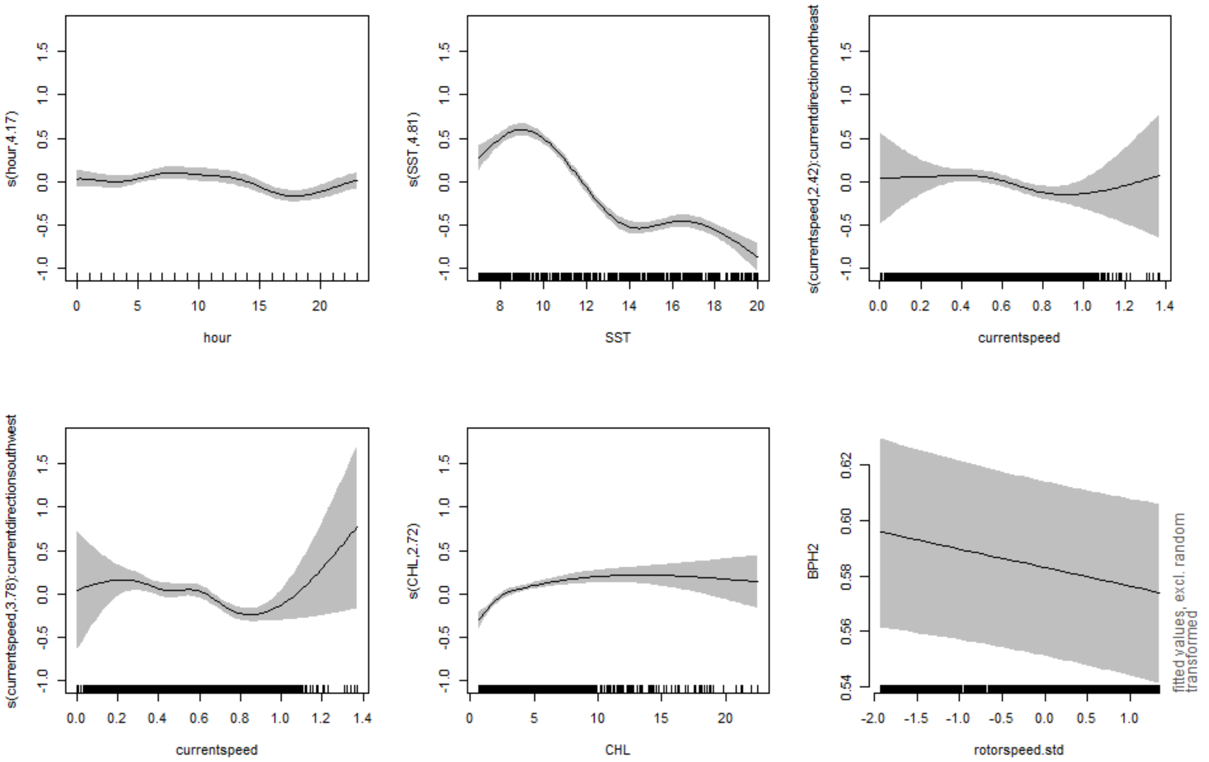
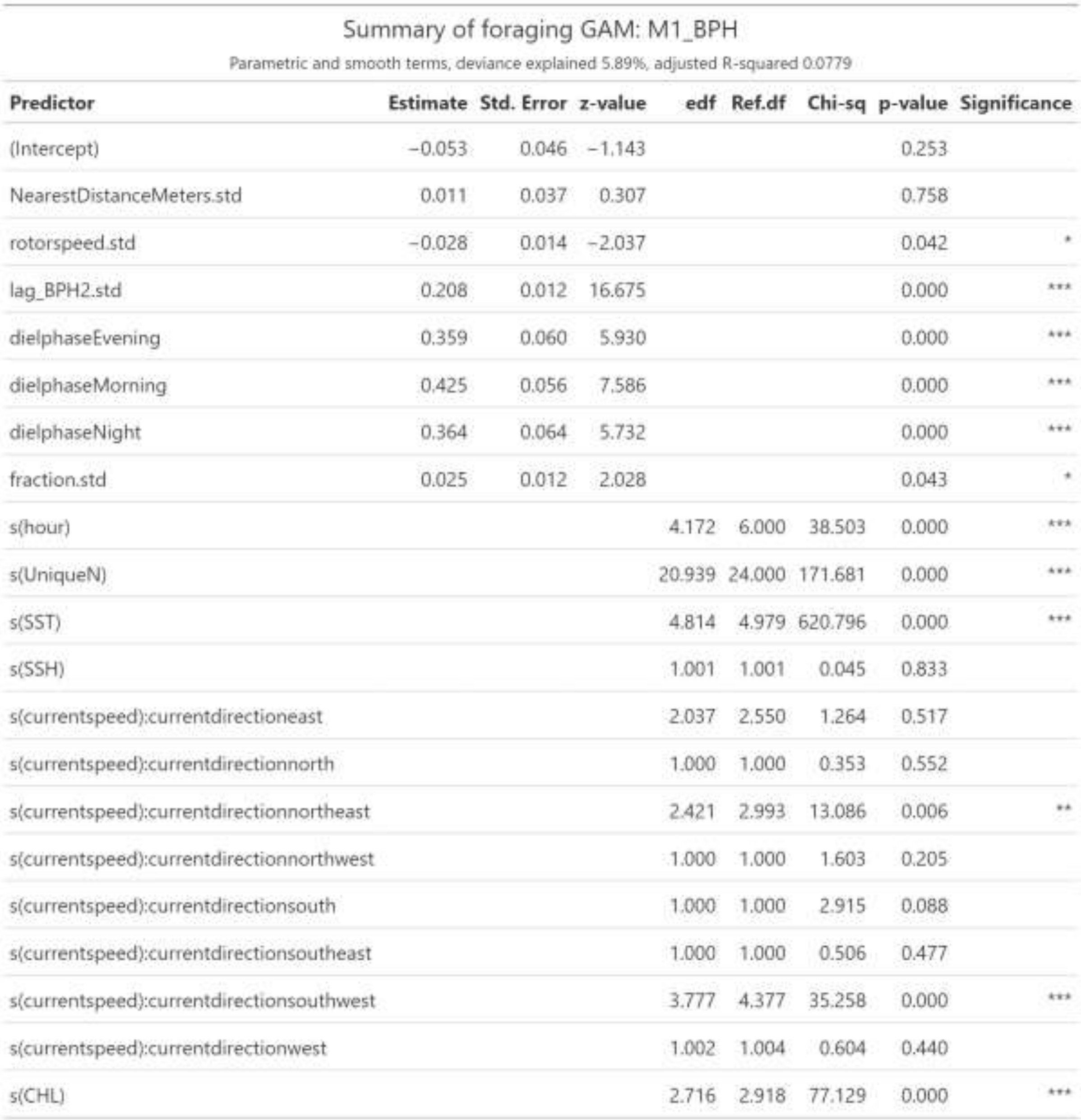


Figure 6 Selection of partial effect plots of explanatory variables, with 95% confidence intervals (grey-shaded areas), selected in the final foraging model. X-axis ticks indicate the spread of the data points used to estimate the partial effect plots.

Table 4 Model summary and outputs of the binomial foraging model.



Summary of foraging GAM: M1_BPH

Parametric and smooth terms, deviance explained 5.89%, adjusted R-squared 0.0779

Predictor	Estimate	Std. Error	z-value	edf	Ref.df	Chi-sq	p-value	Significance
(Intercept)	−0.053	0.046	−1.143				0.253	
NearestDistanceMeters.std	0.011	0.037	0.307				0.758	
rotorspeed.std	−0.028	0.014	−2.037				0.042	*
lag_BPH2.std	0.208	0.012	16.675				0.000	***
dielphaseEvening	0.359	0.060	5.930				0.000	***
dielphaseMorning	0.425	0.056	7.586				0.000	***
dielphaseNight	0.364	0.064	5.732				0.000	***
fraction.std	0.025	0.012	2.028				0.043	*
s(hour)				4.172	6.000	38.503	0.000	***
s(UniqueN)				20.939	24.000	171.681	0.000	***
s(SST)				4.814	4.979	620.796	0.000	***
s(SSH)				1.001	1.001	0.045	0.833	
s(currentspeed):currentdirectioneast				2.037	2.550	1.264	0.517	
s(currentspeed):currentdirectionnorth				1.000	1.000	0.353	0.552	
s(currentspeed):currentdirectionnortheast				2.421	2.993	13.086	0.006	**
s(currentspeed):currentdirectionnorthwest				1.000	1.000	1.603	0.205	
s(currentspeed):currentdirectionsouth				1.000	1.000	2.915	0.088	
s(currentspeed):currentdirectionsoutheast				1.000	1.000	0.506	0.477	
s(currentspeed):currentdirectionsouthwest				3.777	4.377	35.258	0.000	***
s(currentspeed):currentdirectionwest				1.002	1.004	0.604	0.440	
s(CHL)				2.716	2.918	77.129	0.000	***

Discussion

This study investigated the influence of operational OWF turbines on harbour porpoise presence and foraging behaviour in the BPNS. Overall, the results indicate that while environmental and temporal factors were the primary drivers of porpoise occurrence and behaviour, operational wind farm effects were present but spatially structured, relatively subtle and context-dependent, especially for harbour porpoise presence.

4.4. Effects of operational offshore windfarms on harbour porpoise presence

The most prominent pattern in the presence model was the effect of distance to the closest turbine, which showed a significant, and negative relationship with porpoise presence, indicating a higher probability of occurrence closer to turbines. This suggests that, at a fine scale, harbour porpoises do not avoid operational wind farms and show increased use of areas closer to the turbines.

Secondly, a significant interaction between rotor speed and distance to the closest turbine provided further insight into fine-scale habitat use. At close distances, increasing rotor speed was associated with a decrease in the probability of porpoise presence, whereas this effect diminished with increasing distance. At intermediate distances, low rotor speeds also appeared to correspond with reduced presence, indicating that the interaction is not strictly linear and may reflect more complex behavioral responses. This suggests that operational turbine effects are spatially limited and may primarily influence porpoises in the immediate vicinity of turbines (Tougaard et al., 2020; Tougaard, Henriksen, et al., 2009). Despite this significant interaction, rotor speed on its own was not a significant predictor, indicating that turbine-related disturbance does not extend far into the surrounding environment, consistent with previous findings from Tougaard that detection of turbine noise by porpoises is limited to relatively short distances up to 70 m (Tougaard, Henriksen, et al., 2009).

Overall these patterns suggest that the influence of operational windfarms on harbour porpoise presence is not indicative of avoidance and may be locally positive. This aligns with previous studies suggesting that, unlike construction activities such as pile driving (Benhemma-Le Gall et al., 2021; M. Brandt et al., 2018; Carstensen et al., 2006; Norro et al., 2010; Schaffeld et al., 2020; Tougaard, Carstensen, et al., 2009), the operational phase of wind farms has relatively minor impacts on marine mammals (Collier et al., 2022; Diederichs et al., 2008; Rose et al., 2025; Vallejo et al., 2017; van Polanen Petel et al., 2012).

One likely explanation is the exclusion of fisheries and restriction of vessel traffic within wind farm areas (RD 4 Feb 2020 Safety Zones Marine Areas, 2020; RD Marine Spatial Plan 2026-2034, 2026), which reduces disturbance and may allow prey populations to recover (Buyse et al., 2023; Lindeboom et al., 2011; Wilhelmsson et al., 2006). Additionally, turbine foundations and associated scour protection can function as artificial reefs, increasing local biodiversity, productivity and prey availability up to 250 m from the turbines (Bergström et al., 2013; Coates et al., 2016; Dannheim et al., 2025; Fernandez-Betelu et al., 2022; Glarou et al., 2020; van Hal et al., 2017). These mechanisms may partially offset negative effects of turbine noise and could explain why porpoises are frequently detected within and near wind farm areas, a pattern also observed for other artificial structures such as gas and oil rigs (Clausen et al., 2021; Fernandez-Betelu et al., 2022; V. L. G. Todd et al., 2009).

The absence of increased porpoise presence at greater distances from turbines suggests that factors other than the operational wind farms may also be influencing spatial patterns. If avoidance of turbine noise were the main driver, higher occurrence would be expected further away. Instead, lower presence at larger distances may reflect the influence of other anthropogenic pressures. In particular, areas further from turbines, often located near the edges of wind farm zones, may be closer to shipping lanes or transit zones for maintenance vessels (Figure 1), where continuous vessel traffic generates elevated noise levels. While general vessel traffic is restricted within the wind farm zone, these peripheral areas can still experience relatively higher levels of traffic compared to the OWF interior zone. Shipping noise has been shown to negatively affect harbour porpoise behaviour and habitat use (Dracott et al., 2025; Dyndo et al., 2015; Wisniewska et al., 2018), and may therefore counteract any potential increase in presence away from turbines. This suggests that porpoises are responding to a complex acoustic and ecological landscape, where multiple stressors interact to shape their distribution (Frankish et al., 2023; Haelters et al., 2011; Pigeault et al., 2024).
Current speed, sea surface height and chlorophyll were identified as significant predictors for harbour porpoise occurrence, often linked to increased primary productivity and prey behaviour (IJsseldijk et al., 2015; N. R. E. Todd et al., 2022; Zein et al., 2019). However, no clear or consistent patterns were observed in the present study. Additionally, presence probability decreases significantly for all current directions except south, southeast and east. This could potentially be linked to primary productivity but also to the wakes created by the turbines leading to an increase in suspended matter, turbidity and changes in current velocities

(Bailey et al., 2024; Christiansen et al., 2023; Schultze et al., 2020). However the influence of such wake effects on top predators such as harbour porpoises remains poorly understood. Most important factors from the model were the temporal variables, the lagged variable for porpoise occurrence DPH explained a large proportion of porpoise occurrence, confirming the assumption that when a porpoise is present at hour X it is more likely to be present at hour X+1 compared to another random hour. Diel phase evening was also significant, indicating a higher probability of occurrence during the evening compared to the day. This aligns with many studies that have also found less occurrence during the day compared to other diel phases often linked to prey behaviour or diel vertical migration (Fernandez-Betelu et al., 2022; Osiecka et al., 2020; Schaffeld et al., 2016; V. L. G. Todd et al., 2009).

4.5. Effects of operational offshore windfarms on harbour porpoise foraging behaviour

The distinction between presence and foraging behaviour provides further insight into porpoise responses within operational offshore windfarms. While presence patterns showed a clear response in distance to the closest turbine, foraging behaviour appeared to be more strongly driven by temporal and environmental variables such as sea surface temperature, diel phase, and chlorophyll concentration. This suggests that habitat quality and prey availability play a key role in determining foraging activity.

Unlike the presence model, distance to turbine was not identified as a significant predictor of foraging behaviour, and the overall proportion of foraging activity remained relatively consistent across the distance gradient. This indicates that, although porpoises occur near turbines, these areas do not appear to strongly enhance or reduce feeding activity at the scale considered in this study. This may be partially explained by the exclusion of fishing within the windfarm areas (Bicknell et al., 2025; Glarou et al., 2020; Scheidat et al., 2011; van Hal et al., 2017), which may promote a more homogeneous distribution of prey across the windfarm, allowing harbour porpoises to forage throughout the offshore wind farm zone rather than concentrating at specific distances.

No significant interaction between rotor speed and distance was retained in the final foraging model, and the effect of rotor speed itself was small, though statistically significant. Increasing rotor speed was associated with a slight decrease in the probability of foraging occurrence, suggesting a weak negative influence of turbine operation on feeding behaviour. As foraging requires continuous acoustic sampling of the environment, even low levels of noise may interfere with prey detection or capture efficiency (DeRuiter et al., 2009; Miller, 2008). However, the magnitude of this effect was limited, indicating that operational disturbance does not strongly constrain foraging activity.

The dominant role of environmental variables in the foraging model indicates that prey availability and habitat conditions are the primary drivers of feeding behaviour. In particular, sea surface temperature and chlorophyll concentration showed significant relationships with foraging activity, suggesting that porpoises respond strongly to underlying ecosystem productivity and associated prey dynamics (Akimova et al., 2016; Hedger et al., 2004; Sveegaard et al., 2012). The relationship with sea surface temperature was consistent with the observed seasonal pattern in foraging activity, which peaked during winter and spring when temperatures were generally below 12°C. Similar seasonal associations have been reported by Todd et al. (2022), supporting the idea that porpoise foraging activity increases under cooler conditions, likely reflecting shifts in prey availability. These findings are consistent with the role of harbour porpoises as opportunistic predators that exploit a wide range of prey species and respond to fine-scale spatial and temporal variability in their environment (Booth, 2020; Jansen et al., 2013; Leopold et al., 2015). Similarly, the proportional increase in foraging during autumn compared to presence (Figure 3) could be to build up a blubber layer to prepare for the decreasing temperatures in winter and spring (Rojano-Doñate et al., 2018).

While the diel pattern wasn't as apparent in harbour porpoise occurrence, foraging occurrence varying significantly throughout the day and showed increased foraging outside of daytime conditions consistent with several other studies linking it to potential prey avoidance behaviour (Carlstrom, 2005; Schaffeld et al., 2016; N. R. E. Todd et al., 2022; V. L. G. Todd et al., 2009). This pattern has been found to be more pronounced around artificial offshore structures (M. J. Brandt et al., 2014; Fernandez-Betelu et al., 2022).

Current speed on its own was not a significant predictor, however the interaction between current speed and current direction revealed a positive effect for increasing current speeds flowing towards the southwest or northeast.

4.6. Limitations and future implications

Several limitations should be considered when interpreting these results. The use of rotor speed as a proxy for operational noise does not fully capture the complexity of the acoustic environment. Other unmeasured noise sources, such as crew transfer vessels or maintenance vessels, may have contributed to observed patterns, particularly, given the well-documented influence of vessel noise on harbour porpoise behaviour (Basan et al., 2025; Dracott et al., 2025; Dyndo et al., 2015; Wisniewska et al., 2018).

Importantly, the use of binary response variables for both presence (DPH) and foraging (BPH), limits the interpretation of intensity or activity. In particular, the foraging model captures only the occurrence of foraging attempts within an hour and does not account for variation in foraging effort or prey capture success. A detected buzz represents a foraging attempt rather than a successful feeding event (DeRuiter et al., 2009; Pirotta et al., 2014; Schaffeld et al., 2016). Therefore, while no spatial differences in foraging occurrence were observed, it remains possible that finer-scale patterns in foraging effort or success exist but are not captured by this binary metric.

Additionally, although some effects were statistically significant, their magnitude was relatively small, indicating that ecological relevance should be interpreted with caution. Finally, spatial and temporal variability between monitoring locations, captured in part by random effects and smooth terms, suggests that local conditions play an important role in shaping porpoise responses.

Despite these limitations, the study suggests that operational offshore wind farms have neutral and potentially locally positive effect on harbour porpoise presence, while effects on foraging behaviour remain limited and primarily environmentally driven, in particular at small spatial scales similar to what was found in other studies (Collier et al., 2022; Diederichs et al., 2008; Rose et al., 2025; Scheidat et al., 2011; Vallejo et al., 2017; van Polanen Petel et al., 2012). Rather than causing large-scale displacement, turbines appear to induce subtle behavioral adjustments that are mediated by distance and environmental context. This pattern is less clear when looking at foraging behaviour where distance does not seem to impact the occurrence of foraging inside the offshore windfarm but rotor speed does have a small but measurable effect. The coexistence of potential negative effects (e.g., noise) and positive effects (e.g., increased prey availability through the artificial reef effect and reduced fishing pressure) highlights the complexity of porpoise responses to operational offshore wind farms but also highlights the importance of environmental patterns such as diel phases and seasonal occurrence.

Future research should aim to better disentangle these mechanisms by incorporating direct measurements of underwater noise alongside environmental and behavioral data. Incorporating a larger gradient to include areas both outside and inside of the OWF zone and combining this with acoustic noise recordings to characterize the environment and see what other noise effects could be influencing harbour porpoise foraging and behaviour, such as vessel noise amongst other anthropogenic factors and environmental variables such as currents and wind speeds (Basan et al., 2024; Kok et al., 2021). In addition, the use of higher-resolution behavioral metrics, such as foraging intensity (e.g., buzz rates), combined with prey distribution data and fine-scale movement tracking, would provide a more comprehensive understanding of habitat use.

As offshore wind development continues to expand in the North Sea, understanding these nuanced responses will be critical for effective marine spatial planning and conservation. In this context, this study provides insights directly relevant to conservation and management within European frameworks, such as the Habitats Directive and ASCOBANS.

5. DISSEMINATION AND VALORISATION

The results of both studies contribute to the overarching research within the PURE WIND project and have been disseminated through internal project meetings and reporting deliverables. Preliminary findings have been presented to project partners, the public through social media videos and the scientific community through posters and presentations.

Poster & speed talk by Sofya Aoufi during the VLIZ Marine Science Day on 06/03/2024: "Determining the effects of operational offshore wind farms on harbour porpoise distribution and foraging behaviour in the North Sea" directed at the scientific public to outline the research design and methods. VMSD24_BookofAbstracts.pdf

Social media video by Bob Rumes on 06/12/2024 : "Wind farm noise impacts North Sea marine mammals" https://youtu.be/1wyrAwgwlt0?si=CFuwisY3S132s_Ak directed at the wider audience.

Presentation short talk by Sofya Aoufi during the European Cetacean Society Conference 2025 in Ponta Delgada Azores on 25/05/2025: "A comparative review on foraging behaviour methods" 36_ECS_Azores_abstractbook_2025.pdf directed at the scientific community.

Presentation Pitch by Sofya Aoufi during the Offshore wind PhD day at Rodebol Events Ghent, Belgium on 24/09/2026: "Determining the effects of operational offshore wind farms on harbour porpoise distribution and foraging behaviour in the North Sea". Belgian Offshore Wind PhD Day 2025 directed at people working on various aspects of offshore wind energy.

Presentation during the VLIZ PhD symposium Ostend, Belgium by Sofya Aoufi on 06/02/2026: "Effect of anthropogenic noise and changed habitat on harbour porpoise's". presenting part of the PhD research conducted as part of the PURE WIND project to other PhD's and researchers.

Presentation during the VLIZ Marine Science Day by Annelore Van Nieuwenhove on 04/03/2026: "Harbour porpoise distribution near operational offshore windfarms, a passive acoustic monitoring approach". Presenting part of deliverable 3.6 as part of the PURE WIND project to the scientific community. vmsd2026_boa_fin.pdf

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During the PUREWIND project, datasets have been exchanged with project partners leading to additional publications.
They are presented in table A.

Start Date	*Instrument type*	*End Date*	*location*	*Partner receivinbg data*
16/6/2016	AURAL M2	24/08/2016	CPOWER 51°23,3 N 2°26,3 E	University Genova&UMG Poland
21/10/2023	ST500	18/01/2024	belwind C3-D3_D4-C4	NTNU
27/04/2023	ST500	14/07/2023	belwind C3-D3_D4-C4	NTNU
17/09/2023	Temperature	31/11/2023	belwind BBB8 -10 m	CNR
1709/2023	ADCP	31/11/2023	NW2	CNR

Table A: Shared datasets with PUREWIND partners during the project

Participation in tasks and deliverables of the project.

Participation in Tasks and Deliverables

T1.1. Project management

T1.2. Data sharing and result dissemination

T2.1 Sound acquisition from fixed and floating offshore wind farms (OWF)

T2.2 Radiated noise characterisation

T2.5 Outreach and data dissemination

D.2.1 Report on the methodology for data acquisition and the field campaigns executed

D2.3 - Report on characterisation and the influence of type of foundation on the operational sound emissions of fixed windfarms

T3.3. Determination of harbour porpoise activities in operational OWF

T3.5. Parametrization of factors correlated with animal responses to OWF

T3.6. Assessment of impacts of OWF on top predators

The research provides novel insights into the fine-scale behavioural responses of harbour porpoises to operational offshore wind farms. The findings are directly relevant for environmental impact assessments and marine spatial planning in the North Sea.

The results suggest that operational wind farms do not lead to large-scale displacement of harbour porpoises, effects of turbine operation are local and context-dependent, and environmental drivers remain the dominant factors influencing behaviour.

These findings can support evidence-based policy under frameworks such as the Habitats Directive and ASCOBANS, Improved assessment of cumulative impacts of offshore wind expansion, and the development of mitigation strategies that consider both noise and ecological context.

Furthermore, the methodological approach combining passive acoustic monitoring with environmental and turbine operational data provides a transferable framework for future monitoring programmes.

6. PUBLICATIONS

Aoufi S., Rumes, B., Vanaverbeke J., Degraer S., Debusschere E. (2026). A comparative assessment of novel and established methods to infer harbour porpoise foraging behaviour from acoustic data [Manuscript submitted for publication].

Aoufi S., VanNieuwenhove A., Rumes B., Debusschere E., Vanaverbeke J., Degraer S. Impacts of operational offshore windfarms on harbour porpoise presence and foraging behaviour. In prep.

Norro, 2026. Underwater sound generated by an operational wind farm, revisiting the Belgian North Sea case. In prep.

Enhancing our understanding of the impacts of operational noise from offshore wind farms on the marine environment, Impact of sound from Offshore wind farms by Sara Pensieri and Ana Sirovic and Purewind consortium in Hydro International Issue 2 , Vol 28 2024

Justine Courboulès, Tanguy Soulié , Emilie Rojas, Alain Norro, Nicole Aberle, Ana Širović : 2025. Response of natural planktonic communities to low-frequency sounds from offshore windfarms: an in-situ experiment in Norwegian coastal waters, in prep.

Sidonie Rousseau, Justine Courboulès, Fabio Viotti, Erin Murray, Renate Sæther Flister, Saskia Kühn, Malien Laurien, Ana Širović, Dag Altin, Nicole Aberle, Alain Norro, Kang Nian Yap: 2025
Physiological and behavioural effects of offshore wind farm sounds on the copepod Calanus finmarchicus [Manuscript submitted for publication].

Fabio Viotti, Saskia Kuhn, Sidonie E.J. Rousseau , Erin Murray , Justine Courboules , Tanguy Soulie, Dag Altin , Alain Norro , Nicole Aberle , Ana Sirovic , Kang Nian Yap , Katja Heubel :2026 . Response of wild and cultured calanoid copepods to chronic anthropogenic noise submitted to Frontiers in marine sciences 2026

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ANNEXES

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