CHAPTER 3

FIT FOR PORPOISE? ASSESSING THE EFFECTIVENESS OF UNDERWATER SOUND MITIGATION MEASURES

Bob RUMES & Steven DEGRAER

Royal Belgian Institute of Natural Sciences (RBINS), Operational Directorate Natural Environment (OD Nature), Aquatic and Terrestrial Ecology (ATECO), Marine Ecology and Management (MARECO), Vautierstraat 29, 1000 Brussels, Belgium

Corresponding author: bob.rumes@naturalsciences.be

Abstract

In this chapter, we review how developers complied with the environmental license conditions formulated to mitigate the potential negative impacts of pile driving on marine mammals in the Belgian part of the North Sea (BPNS), whether this impacted the timing of development and what the likely consequences were for marine mammals. Between 2009 and 2020, offshore wind farm developers in the BPNS complied to a large extent with those environmental license conditions formulated to mitigate the potential negative impacts of pile driving on marine mammals. However, we did identify several possible improvements to these environmental license conditions, including changes in the use of acoustic deterrent devices, formalising obligatory mammal surveys, and requiring developers to comply with the national threshold for impulsive underwater sound. The reduction in the costs of applying noise mitigation measures ensures that these suggested improvements should not affect the economic viability of future projects.

1. Introduction

In December 2000, the first offshore wind farm (OWF) in the North Sea became operational. It was located 1.6 km off the coast of Blyth, England and comprised two 2 MW turbines. Since then, offshore wind in the North Sea has grown with leaps and bounds, and 20 years later the North Sea has a total installed capacity of 22 GW. This growth is expected to accelerate as, in order to meet the EU objective of reaching net-zero greenhouse gas emissions by 2050, offshore wind capacity in the North Sea should increase to a total installed capacity of at least 150 GW in the next thirty years (North Seas Energy Cooperation 2020). The installation of wind turbines, electric transformer stations and power cables in the marine environment has a range of environmental effects which depend among others on the location, timing and methods of installation (Lindeboom *et al.* 2011; Degraer *et al.* 2013). Prior to installing a renewable energy project in the North Sea, a developer must obtain an environmental permit (see chapter 1

Table 1. Overview of environmental permit conditions for hydraulic pile driving in the Belgian part of the North Sea (2004-2015)

<table>
<tr><th>Project name</th><th>Environmental permit granted</th><th>Use of Acoustic Deterrent Device</th><th>Marine mammal survey prior to pile driving</th><th>Seasonal pile driving ban from January 1st to April 30th</th><th>Noise mitigation measures for impact pile driving*</th><th>Start pile driving</th><th>Pile driving events*</th></tr>
<tr><td>C-Power</td><td>14-04-2004

Modified 25-04-2008</td><td>“to be used at least half an hour prior to the start of pile driving”

“starting one hour before up to the start of pile driving”</td><td>No

Yes, “half an hour prior to the start of activities”</td><td>No

No, but an additional cost applies when pile driving in this period</td><td>No</td><td>07-04-2011</td><td>54</td></tr>
<tr><td>Belwind</td><td>20-02-2008</td><td rowspan="4">“starting one hour before up to the start of pile driving”</td><td rowspan="3">Yes, “half an hour prior to the start of activities”</td><td rowspan="3">No, but an additional cost applies</td><td rowspan="3">No</td><td>07-09-2009</td><td>67</td></tr>
<tr><td>Northwind</td><td>19-11-2009</td><td>07-04-2013</td><td>73</td></tr>
<tr><td>Nobelwind</td><td>13-05-2015</td><td>16-05-2016</td><td>51</td></tr>
<tr><td>Norther</td><td>18-01-2012</td><td rowspan="5">Yes, “before and during pile driving activities”</td><td rowspan="5">Yes</td><td rowspan="2">SBBC</td><td>06-08-2018</td><td>45</td></tr>
<tr><td>Rentel</td><td>08-02-2013</td><td rowspan="4">“starting half an hour before up to start of pile driving”</td><td>21-07-2017</td><td>43</td></tr>
<tr><td>SeaMade</td><td>07-02-2014 (Seastar)

13-04-2015 (Mermaid)</td><td rowspan="2">DBBC</td><td>08-09-2019</td><td>60</td></tr>
<tr><td>Northwester 2</td><td>18-12-2015</td><td>29-07-2019</td><td>24</td></tr>
<tr><td>Elia MOG</td><td>07-07-2014</td><td>GABC</td><td>04-11-2018</td><td>3</td></tr>
</table>

* A pile driving event refers to any instance where hydraulic pile driving takes place after a period of at least three hours of no pile driving. Therefore, the installation of a single turbine foundation can comprise multiple pile driving events. A short description of the noise mitigation measures is provided in the results section.

** All environmental permits also require the developer to use a ‘ramp-up’ or ‘soft start’ procedure at the start of pile driving. In this case, lower hammer energy levels are used to start the pile driving process, and then the force of pile driving is gradually increased.

of this report), which includes terms and conditions intended to minimise and/or mitigate the impact of the project on the marine ecosystem. Some of the mitigation measures formulated to reduce the impact of OWF construction on marine mammals are considered onerous by developers as they increase project cost both directly (*i.e.* the cost of the mitigation measures) and indirectly (by increasing construction time; Koschinski & Lüdemann 2013). In addition, there is a discussion as to whether the benefits of using of an Acoustic Deterrent Device (ADD) to scare away marine mammals prior to pile driving outweigh the negative consequences of thereby prolonging the introduction of high levels of underwater sound into the marine environment (Graham *et al.* 2019; Rose et *al.* 2019). Given that construction activities in the first Belgian offshore energy zone have come to an end, and that new mitigation measures need to be prepared in anticipation of the licensing of the second Belgian offshore energy zone (see chapter 1 in this report), now is a good time to evaluate those mitigation measures formulated to reduce the impact of pile driving on marine mammals.

In this paper we combined data from developers and regulators to analyse whether developers complied with the environmental license conditions formulated to mitigate the potential negative impacts of pile driving on marine mammals in the Belgian part of the North Sea (BPNS), how this impacted the timing of development and what the likely consequences were for marine mammals.

2. Material and methods

2.1. Data acquisition and analysis

Using the website of the Scientific Service Management Unit of the Mathematical Model of the North Sea (MUMM: https://odnature.naturalsciences.be/mumm/en/windfarms/), we accessed the environmental permits of the nine wind farms and the offshore switchyard platform that engaged in pile driving activities in the BPNS in the period 2009-2020 (permits granted 2004-2015). Prior to 2009, no pile driving occurred in the BPNS. Those terms and conditions in the environmental permits that were intended to minimise and/or mitigate the impact of OWF construction on marine mammals are listed below (table 1). Initial permit conditions were aimed at preventing near-field injury to

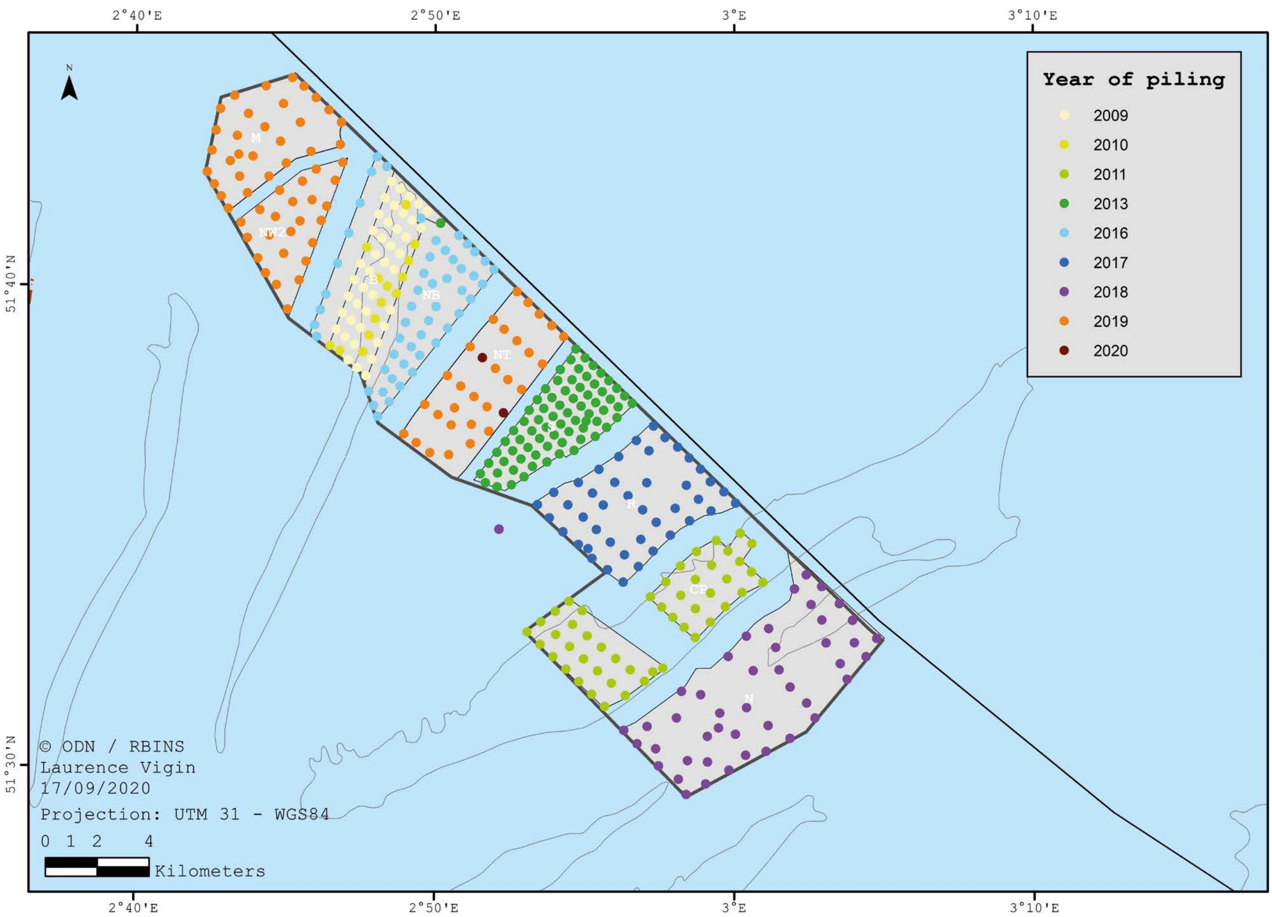

Figure 1. Timing and location of pile driving events in the Belgian part of the North Sea (period 2009-2020, data RBINS).

individual animals, and included the use of an acoustic deterrent device (ADD) as well as a prohibition on starting pile driving if a marine mammal was observed in the vicinity of the construction zone. Progressive insight in the potential population consequences of far-field behavioural disturbance resulting from exposure to excessive levels of impulsive underwater sound led to the formulation of further permit conditions. These included a seasonal pile driving ban from January 1st to April 30th, and an obligation to use noise mitigation measures that limit the transmission of noise pollution to the marine environment. All permits also included an obligation to use a soft start or ramp up method, whereby a pile is initially driven with low hammer energy which is gradually increased with increasing soil penetration. Since a soft start is an operational necessity for pile driving, we don't consider it as a real mitigation measure for the purposes of this paper.

Compliance of the developer with these conditions was checked based on the information provided by the developer in the daily reports on piling activities and confirmed by the aerial surveillance program as well as the environmental monitoring conducted, both coordinated by the Operational Directorate Natural Environment of the Royal Belgian Institute of Natural Sciences. The timing and location of pile driving events in the BPNS are shown in fig. 1.

The interim Population Consequences of Disturbance (iPCOD) model was developed to assess the potential effects of anthropogenic noise, associated with offshore renewable energy developments, on harbour porpoise populations (Harwood *et al.* 2013; Nabe-Nielsen & Harwood 2016). In this model population dynamics are simulated based on the birth and average survival rates of harbour porpoises in the North Sea, derived from expert elicitation (Booth *et al.* 2019; Sinclair *et al.* 2019). In this report, we used the latest update of the iPCOD model (version 5.2 – released on 2 October 2019) to compare the consequences of the realised pile driving activities in the BPNS (2009-2019) on a local population of harbour porpoise under three scenarios': without any mitigation measures (no mitigation), a second scenario with the applied mitigation measures (as-it-happened) accounting for the applied mitigation measures, and accounting for the observed reductions in underwater sound (as reported in Norro 2018, 2019 and this report), and a final scenario (optimal configuration) in which the most successful combination of mitigation measures (as applied for NW2 in 2019; Norro, this volume) is assumed for all OWF construction in the BPNS. For an overview of the input parameters, and underlying assumptions used in these scenarios': see Rumes & Debusschere (2018). In theory each pile driving event could lead to two residual days of disturbance as the reduction of detection rates has been observed starting one day before and up to two days after pile driving (Brandt *et al.* 2016; Rumes *et al.* 2017). However, given the nature of the actual piling calendars – with piling activities often taking place less than 24 h after the previous event – it was decided that each day with pile driving could lead to only one residual day of disturbance. Every scenario was simulated 1000 times.

Statistical analyses and coding were performed in the Rstudio environment under R version 4.0.0. Plots were generated in Rstudio using both the lattice and ggplot2 packages.

3. Results

3.1. Compliance

3.1.1. Use of Acoustic Deterrent Device

Seal scarers were originally designed to deter seals from fishing gear and aquaculture installations to avoid depredation on fish. In the context of OWF construction, they can be referred to as both acoustic deterrent devices (ADDs) and acoustic harassment devices (AHDs). ADDs transmit short sounds in a frequency range of 10-40 kHz (most often

Figure 2. Lofitech Acoustic Deterrent Device of the type used during the construction of the Belwind wind farm. The figure shows the control unit (left) and transducer (on the right). The control unit contains a pulse generator and an amplifier and transmits random bursts of audio frequency signals to the transducer, where they are converted into intense sound (from www.seiche.com).

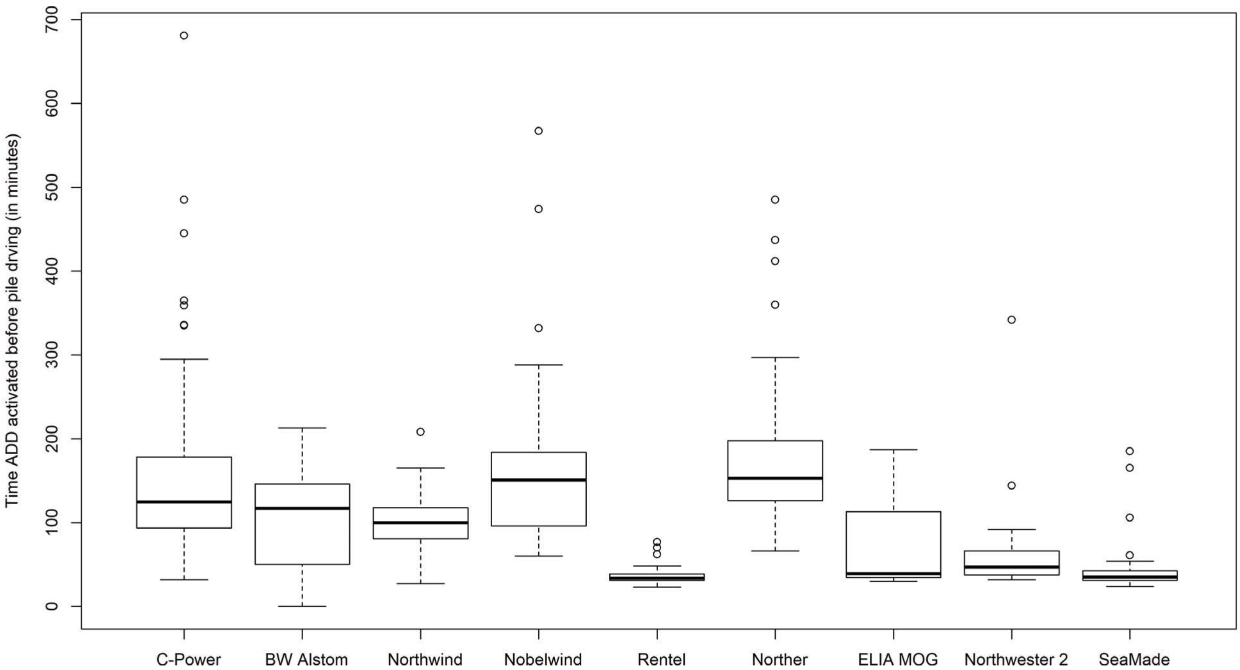

Figure 3. Timing of ADD activation relative to the start of hydraulic pile driving.

with main energy at 10-14 kHz). The length of pulses and intervals between them are often randomised to decrease the potential for animals habituating to the sounds, so that aversion effects can be maintained over time (Hermannsen *et al*. 2015). In compliance with their environmental permit, all developers reported on the use of ADDs prior to the start of pile driving. The devices used were approved by MUMM prior to deployment. Most projects used a LofiTech Seal scarer which operates at a frequency of 14 kHz (fig. 2). For the Norther project a FaunaGuard was used which operates at frequencies of 60-150 kHz and is designed to deter harbour porpoises. The different sounds are based on the hearing range and sensitivity of this species (frequency spectrum) and the reaction threshold levels, based on known literature and extensive behavioural response experiments (Van der Meij *et al.* 2015). As stipulated in the permit conditions, the ADDs had a source level of 170 to 195 dB_{p-p} re 1 µPa. In practice, ADDs were often activated well before pile driving started and they were used for a much longer period than anticipated (fig. 3, data on ADD activation was not available for the Belwind project). In some extreme cases, this was due to technical difficulties preventing the start of hydraulic pile driving. On average ADD deployment lasted for 134 minutes (SD: 109 minutes). In only two instances the ADD was not used. In a few instances, the ADD was only turned off hours after pile driving was ended resulting in a significant prolongation of the period of acoustic disturbance.

3.1.2. Marine mammal survey prior to pile driving

Based on the daily reports provided by the developers, a watchman conducted a marine mammal survey prior to pile driving whenever this was possible (daylight hours). No marine mammals were observed by the watchmen nor was any mortality of animals (fish, seabirds, squids, or marine mammals) reported. As a consequence, at no point was pile driving delayed due to the presence of marine mammals in the vicinity of the pile driving platform.

3.1.3. Seasonal pile driving ban from January 1st to April 30th

As of 2013, the environmental permit of new projects included a seasonal ban on hydraulic pile driving in Belgian waters from January 1st to April 30th in order to avoid the period with consistently highest local harbour porpoise densities. This was respected by all projects, except for the Seamade project that installed its last two turbine foundations on January 1st and 2nd 2020 after obtaining a derogation from the Minister.

3.1.4. Noise mitigation measures for impact pile driving

Concern over the high levels of underwater noise being generated during pile driving operations for the building of the first OWFs (Norro *et al.* 2010, 2013) and the observed large scale avoidance of the construction zone by porpoises (Haelters *et al.* 2010) has led to the formulation of a threshold for impulsive underwater sound in the BNS at 185 dB re 1 µPa (Sound Pressure Level, zero to peak) at 750 m from the source (Anonymous 2012). In compliance with their environmental permits, since 2017, all subsequent projects have used various types of noise mitigation measures (see table 1) with varying levels of success (Norro 2018, 2019; chapter 2 in this report). These included single big (SBBC), double big (DBBC) and grout annulus bubble curtains (GABC). A bubble curtain is formed around a pile by freely rising bubbles created by compressed air injected into the water through a ring of perforated pipes encircling the pile. A SBBC is a ring of perforated pipes positioned on the sea floor around the foundation to be piled. Compressors located on the construction vessel or on a platform feed air into the pipe. The air passes into the water column by regularly arranged holes. Freely rising bubbles form a large curtain around the entire structure, even in tidal conditions, thus shielding the environment from the noise source (Koschinski & Lüdemann 2013). DBBCs add a second of ring of perforated pipes around a BBC. The GABC is generated by blowing air into the annulus between the skirt sleeve and pin pile of the jacket foundation. Within the annulus, the air bubbles are protected from the current resulting in a stable air-water mixture that acts as an impedance barrier to the pressure waves generated by the pile during each hammer strike. At the top of the annulus, about 10 m above seabed, the bubbles drift out and are subjected to the current, carrying them away from the pile (Lippert *et al.* 2017).

3.2. Effects of mitigation measures on offshore wind farm construction

Since all projects are different in ways that influence the speed of construction (foundation type, soil conditions, weather conditions in the year of installation…) we limited ourselves here to a rough comparison of the average installation time per foundation (installation period divided by the number of installed foundations) for projects with and without noise mitigation measures (table 2). The ELIA MOG project and Belwind Alstom demo turbine could not be included in this comparison as these required the installation of only a single foundation eliminating the need to move the construction vessel and set up noise mitigation measures. Based on the available data, there is no indication that the need for noise mitigation increased installation time for offshore wind projects in the BPNS. In recent years, the overall time needed to install a project's foundations has decreased as fewer, larger turbines are being installed (table 2).

3.3. Population consequences of mitigation for marine mammals

The mean porpoise population decline at the end of the OWF construction period exceeded 1.5% for both the scenario without any mitigation measures as well as the scenario accounting for the applied mitigation measures (fig. 4). For the scenario in which the most successful combination of mitigation measures is assumed for all OWF construction in the BPNS, mean porpoise population decline at the end of the construction period was only 0.1% (table 3). More importantly, relative differences between the scenarios indicate that the applied mitigation measures reduced mean porpoise population decline at the end of the OWF construction period by 50%, and that currently available mitigation measures would have reduced porpoise population decline by 97%.

4. Discussion

4.1. Compliance

4.1.1. Optimising the use of acoustic deterrent devices

ADDs have been widely used during the construction of OWFs in the North Sea in order to make sure that marine mammals vacate the immediate vicinity of construction sites prior to the start of pile driving and thereby avoid near-field injury (JNCC 2010; Hermannsen *et al.* 2015; Brandt *et al.* 2016). Yet, there is increasing evidence that the use of ADDs can cause a prolonged

Table 2. Installation time for offshore wind projects in the Belgian part of the North Sea

Project	Foundations	Start installation	End installation	Noise mitigation	Construction period (days)	Days needed per foundation
Belwind	56	07/09/2009	04/02/2010	None	150	2.7
C-Power	49	04/04/2011	21/08/2011	None	139	2.8
Northwind	73	07/04/2013	09/09/2013	None	155	2.1
Nobelwind	51	16/05/2016	22/09/2016	None	129	2.5
Average	**57.3**				**143.3**	**2.54**
Rentel	43	21/07/2017	23/09/2017	BBC	64	1.5
Norther	45	06/08/2018	12/11/2018	BBC	98	2.2
Northwester 2	24	29/07/2019	13/11/2019	DBBC	107	4.5
Seamade	60	08/09/2019	02/01/2020	DBBC	116	1.9
Average	**43.0**				**96.3**	**2.52**

BBC: Big Bubble Curtain. DBBC: Double Big Bubble Curtain.

Table 3. Overview of the outcome of the three scenarios' simulated with the iPCOD model, showing the mean decrease (%) in porpoise population size at six (end of the first phase of constructions), twelve (end of the second phase of constructions), and twenty-five (end of the simulation) years after the start of the piling calendar

	Mean decline in porpoise population* after			Reduction compared
Scenario	6 years	12 years	25 years	to 'No mitigation'
1. No mitigation	1.81	3.75	3.42	–
2. As-it-happened	0.92	1.88	1.73	50%
3. Optimal configuration	0.04	0.11	0.09	97%

* as compared to an unimpacted population

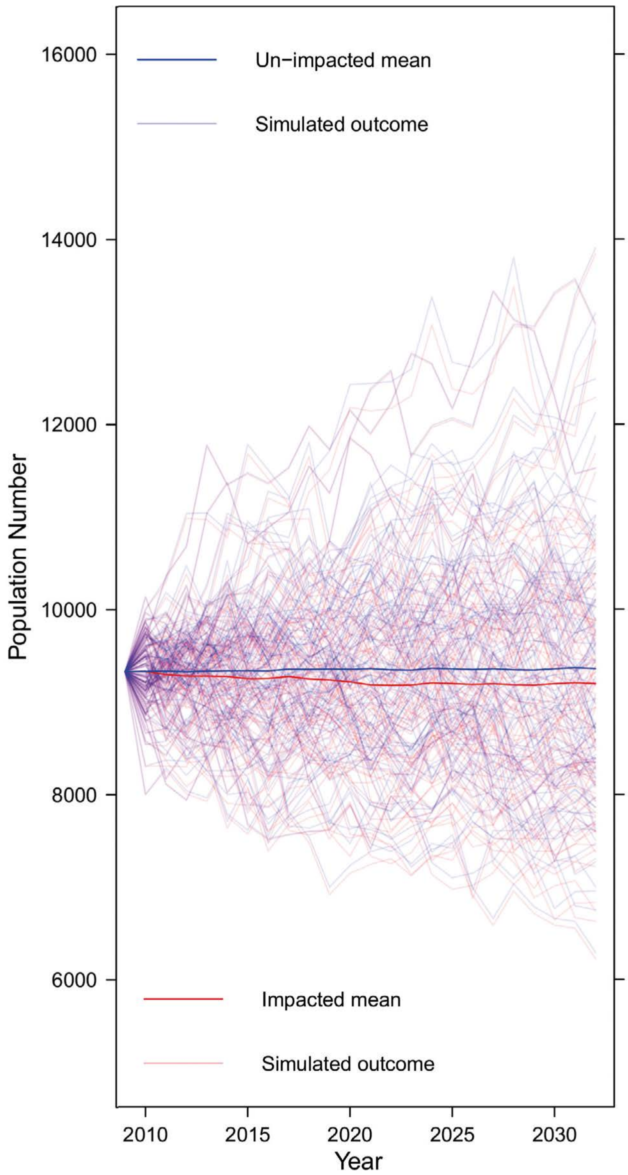

Figure 4. Line plots showing the mean population trajectories and the 1000 simulated populations for the un-impacted population (blue), the impacted population (red), both overlain for scenario 2 with the actually applied mitigation measures showing a decrease in mean porpoise population size of 1.73% after 25 years.

introduction of high levels of underwater sound into the wider marine environment which may have far-field disturbance effects (Brandt *et al.* 2013; Graham *et al.* 2019; Rose *et al.* 2019). The environmental permits include clear guidance on ADD use in order to limit prolonged introduction of high levels of underwater sound: ADDs are to start an hour (permits up to 2012) or half an hour (permits since 2013) before the start of pile driving and are to be shut down when pile driving starts. Even accounting for occasional technical difficulties, for the projects in the BPNS, ADDs were too often turned on too soon and left on longer than needed. It is recommended that for future projects, the timing of any use of ADDs is monitored closely during the construction period allowing for immediate remedial actions. It has also been suggested to use a substantially less powerful pinger as an initial deterrent prior to the use of the ADD (Skjellerup *et al.* 2014). Such a pinger could potentially replace the ADD altogether, as both increased vessel noise (Dyndo *et al.* 2015) and the constant use of sonar by large vessels in the construction zone are likely to have already deterred most nearby porpoises (Rose *et al.* 2019).

4.1.2. Formalising obligatory marine mammal surveys prior to pile driving

Passive acoustic monitoring has shown that there are still porpoises present in the construction zone during foundation installation (Rumes *et al.* 2017). To avoid injuring these animals, pile driving activities cannot commence and must be stopped when a marine mammal is observed at less than 500 m from the construction vessel. The environmental permit requirement to conduct a marine mammal survey prior to pile driving was inspired by the statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise (JNCC 2010). However, in contrast to the aforementioned protocol, it was not required that this survey was conducted by an appropriately trained marine mammal observer (MMO), which may explain why not a single marine mammal was observed during these surveys in the past ten years. For the next project, it is worth having a trained MMO on board conducting regular visual marine mammal surveys and evaluating how this influences detections. In addition to observer training, there are several factors that likely contributed to the fact that no marine mammals were observed, including those that influence both visibility (pile driving at night and during low visibility) and availability (avoidance of work zone due to high vessel activity, low seasonal porpoise densities).

4.1.3. Seasonal pile driving ban from January 1st to April 30th

There is a long history of regulatory agencies using seasonal restrictions on activities to avoid harming marine mammal populations (Richardson 1995). In the North Sea, the Dutch authorities initially banned pile driving for offshore wind farms from January 1st to July 1st (Arends *et al.* 2009), and later moved to a dynamic underwater sound threshold (MEZ 2015). In the BPNS, a seasonal ban on hydraulic pile driving in Belgian waters from January 1st to April 30th has been enforced since 2016. Overall compliance with the seasonal pile driving ban has been very good with (almost) no pile driving taking place in this period of highest local porpoise densities.

4.1.4. Efficient noise mitigation measures are likely to reduce the impact of pile driving

From 2017 onwards, underwater noise mitigation measures were used during pile driving. Unfortunately, there was a lower than expected performance of the SBBC, which is likely due to local hydrodynamic conditions and/or sub-optimal use of the equipment (Norro 2018, 2019). As a result, most projects routinely exceed the national threshold on impulsive underwater sound set at 185 dB re 1 μPa (sound pressure level, zero to peak; SPL_{z-p}) at 750 m from the source (Anonymous 2012). For the last two projects, which used DBBC, the *in situ* measured SPL_{z-p} mostly remained below the national threshold (Norro, chapter 2 in this volume) showing that it is possible to adequately reduce the amount of underwater noise being introduced into the marine environment by using a combination of noise mitigation measures. It is recommended that future projects only be allowed to continue construction after they have demonstrated their ability to comply with national underwater sound regulations using data from the first few pile driving events. Such a regulation is already enforced in two other North Sea countries: Germany (Anonymous 2017) and the Netherlands (MEZ 2015). If these noise mitigation measures result in a meaningful reduction of porpoise displacement range and duration, then it could be considered eliminating the need for a seasonal pile driving ban.

4.2. Effects of mitigation measures on offshore wind farm construction

Noise mitigation measures during pile driving are intended to benefit the marine environment but should not threaten the renewable energy goals by impacting the project's viability. The direct costs of applying noise mitigation measures during pile driving currently are less than € 5m (~0.5% of the construction cost) for an 80 turbine OWF-project (Verfuss *et al.* 2019). This is much lower than the costs in 2011 to 2014, which ranged from € 15m to € 36m for an equally sized OWF (Philipp 2018). Indirect costs associated with the use of noise mitigation measures are assumed to result from prolonged installation schedules and an overall increase in complexity and risk (Verfuss *et al.* 2019). Experiences in the BPNS suggest that the use of noise mitigation did not increase installation time for offshore wind projects. This is likely since SBBCs and DBBCs were used, which can be deployed independently from the installation vessel (Koschinski & Lüdemann 2013). This is in line with results from Germany, where despite a strict noise threshold, wind farm construction has proceeded at pace, even with declining government subsidies (Andresen 2017). This indicates that although the economic cost of compliance with the underwater noise regulations may affect the profitability of offshore wind farms, they have not affected their economic viability (Merchant 2019).

4.3. Population consequences of mitigation for marine mammals

We used the interim Population Consequences of Disturbance model (iPCOD) to simulate how different approaches to noise mitigation during pile driving for offshore construction can impact a harbour porpoise population over a period of 25 years and found that currently available mitigation technologies can avoid 97% of the porpoise population decline anticipated under a 'no mitigation' scenario. Applied mitigation measures are assumed to work in two ways: by reducing the animals experiencing permanent threshold shift through the use of acoustic deterrent devices, and by reducing the number of animals disturbed by impulsive sound by limiting the transmission of sound waves. For similar projects, differences in the configuration and nature of noise mitigation measures resulted in major changes in the size of the area impacted by high levels of impulsive sound (see Norro, chapter 2 of this volume). An optimal configuration of mitigation measures will thus reduce the number of porpoises that are being disturbed by an order of magnitude. However, the assumptions made about the effect of noise mitigation on the (spatial and temporal) magnitude of porpoise disturbance are possibly overly optimistic. In their study of German OWF construction, Rose *et al.* (2019) could not demonstrate a further reduction in displacement of porpoises during construction, despite a considerable improvement in noise-mitigation systems used.

5. Conclusion

Between 2009 and 2020, OWF developers in the BPNS largely complied with the national environmental license conditions formulated to mitigate the potential negative impacts of pile driving on marine mammals. We have identified possible improvements to these environmental license conditions, including optimisation in the use of acoustic deterrent devices, formalising obligatory marine mammal surveys, and requiring developers to comply with the national threshold for impulsive underwater sound. A reduction in the costs of applying noise mitigation measures ensures that the suggested improvements should not affect the economic viability of future projects.

References

Andresen, T. 2017. “Offshore wind farms offer subsidy-free power for first time”. Bloomberg. Available online at: https://www.bloomberg.com/news/articles/2017-04-13/germany-gets-bids-for-first-subsidy-free-offshore-wind-farms

Anonymous, 2012. Omschrijving van goede milieutoestand en vaststelling van milieudoelen voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art 9 & 10. Brussels: BMM, Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, 34 p.

Anonymous, 2017. Offshore wind farms. In-situ determination of the insertion loss of control measures underwater. 24 p. https://dx.doi.org/10.31030/2605437

Arends, E., Groen, R., Jager, T., Boon, A. & Schadek, U. 2009. Passende beoordeling windpark ‘BARD Offshore NL 1’. Report.

Booth, C.G., Heinis, F. & Harwood, J. 2019. Updating the interim PCoD model: workshop report. New transfer functions for the effects of disturbance on vital rates in marine mammal species. Report Code SMRUC-BEI-2018-011, submitted to the Department for Business, Energy and Industrial Strategy (BEIS).

Brandt, M.J., Höschle, C., Diederichs, A., Betke, K., Matuschek, R., Witte, S. & Nehls, G. 2013. Far-reaching effects of a seal scarer on harbour porpoises, *Phocoena phocoena*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 23: 222-232. https://doi.org/10.1002/aqc.2311

Brandt, M.J., Dragon, A., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G., Wahl, V., Michalik, A., Braasch, A., Hinz, C., Ketzer, C., Todeskino, D., Gauger, M., Laczny, M. & Piper, W. 2016. Effects of offshore pile driving on harbour porpoise abundance in the German Bight. Assessment of noise effects. Report by BioConsult SH, IBL Umweltplanung GmbH, and Institute of Applied Ecology (IfAO), 262 p.

Degraer, S., Brabant, R. & Rumes, B. 2013. *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Learning from the Past to Optimize Future Monitoring Programs.* Brussels: Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section.

Dyndo, M.,Wisniewska, D.M., Rojano-Donate, L. & Madsen, P.T. 2015. Harbour porpoises react to low levels of high frequency vessel noise. Scientific reports No. 5.

Isla, M.G. *et al.* 2019. Harbour porpoise responses to pile-driving diminish over time. *Royal Society Open Science* 6 (6), 13 p.

Haelters, J., Kerckhof, F., Vigin, L. & Degraer, S. 2011. Offshore wind farm impact assessment: monitoring of marine mammals during 2010. In S. Degraer *et al.*, *Offshore Wind farms in the Belgian Part of the North Sea: Selected Findings from the Baseline and Targeted Monitoring*. Brussels: Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section, pp. 131-146.

Harwood, J., King, S., Schick, R. Donovan, C. & Booth, C. 2013. A protocol for implementing the interim population consequences of disturbance (PCoD) approach: quantifying and assessing the effects of UK offshore renewable energy developments on marine mammal populations. *Scottish Marine and Freshwater Science* 5 (2), 90 p.

Hermannsen, L., Mikkelsen, L. & Tougaard, J. 2015. Review. Effects of seal scarers on harbour porpoises. Research note from DCE. Aarhus: Danish Centre for Environment and Energy, Aarhus University, 23 p.

JNCC. 2010. Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise. Aberdeen: Join Nature Conservation Committee.

Koschinski, S. & Lüdemann, K. 2013. Development of noise mitigation measures in offshore wind farm construction. Report of the Federal Agency for Nature Conservation.

Lindeboom, H. *et al.* 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters* 1341 (6): 35101-13. https://doi.org/10.1088/1748-9326/6/3/035101

Lippert, S., Huismann, M., Ruhnau, M. von Estorff, O.. & van Zandwijk, K. 2017. Prognosis of underwater pile driving noise for submerged skirt piles of jacket structures. Proceedings of the UACE2017 4th underwater acoustics conference and exhibition.

Merchant, N.D. 2019. Underwater noise abatement: economic factors and policy options. *Environmental Science & Policy* (92): 116-123. https://doi.org/10.1016/j.envsci.2018.11.014

Ministerie van Economische Zaken, 2015. Ontwerpkavelbesluit II windenergiegebied Borssele. 65 p.

Nabe-Nielsen, J. & Harwood, J. 2016. Comparison of the iPCOD and DEPONS models for modelling population consequences of noise on harbour porpoises. Aarhus: Aarhus University, Scientific Report from Danish Centre for Environment and Energy No. 186, 22 p.

North Seas Energy Cooperation, 2020. Joint statement of North Seas countries and the European commission. Brussels: European Commission. Available online at: https://ec.europa.eu/info/news/progress-north-seas-energy-cooperation-2020-jul-06_en

Norro, A., Haelters, J., Rumes, B. & Degraer, S. 2010. Underwater noise produced by the piling activities during the construction of the Belwind offshore wind farm (Bligh Bank, Belgian Marine Waters). In S. Degraer *et al.*, *Offshore Wind Farms in the Belgian Part of the North Sea: Heading for an Understanding of Environmental Impacts*. Brussels: Royal Belgian Institute of Natural Sciences, pp. 37-51.

Norro, A., Rumes, B. & Degraer, S. 2013. Differentiating between underwater construction sound of monopile and jacket foundations for offshore wind turbines: a case study from the Belgian part of the North Sea. *The Scientific World Journal* 5. https://doi.org/10.1155/2013/897624

Norro, A. 2018. On the effectiveness of a single big bubble curtain as mitigation measure for offshore wind farm piling sound in Belgian waters. In S. Degraer *et al.* (eds), *Environmental Impacts of Offshore Wind farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence.* Series 'Memoirs on the Marine Environment'. Brussels: Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section, pp. 19-25.

Norro, A. 2019. On the effectiveness of underwater sound mitigation measures used during pile drivng in Belgian waters. In S. Degraer *et al.* (eds), *Environmental Impacts of Offshore Wind farms in the Belgian Part of the North Sea: Marking a Decade of Monitoring, Research and Innovation.* Series 'Memoirs on the Marine Environment'. Brussels: Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section, pp. 19-25.

Philipp, E. 2018. Noise mitigation in German offshore wind construction since 2014 – practical experience and influence of pile driving on harbour porpoise. Offshore Wind R&D Conference. Bremerhaven: RAVE.

Richardson, W.J., Greene, J.C.R., Malme, C.I. & Thomson, D.H. 1995. *Marine Mammals and Noise*. San Diego: Academic Press, 576 p.

Rose, A. *et al.* 2019. Effects of noise-mitigated offshore pile driving on harbour porpoise abundance in the German Bight 2014-2016 (Gescha 2). Report by IBL Umweltplanung GmbH.

Rumes, B., Debusschere, E., Reubens, J., Norro, A., Haelters, J., Deneudt, K. & Degraer, S. 2017. Determining the spatial and temporal extent of the influence of pile driving sound on harbour porpoises. In S. Degraer (eds), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: A continued move towards integration and quantification*. Brussels: Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section, pp. 129-141.

Rumes, B. & Debosschere, J. 2018. Modelling the impact of pile driving on porpoise populations in the Belgian part of the North Sea. In S. Degraer *et al.*, *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence.* Series 'Memoirs on the Marine Environment'. Brussels: Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section, pp. 117-128.

Sinclair, R., Booth, C., Harwood, J. & Sparling, C. 2019. Helpfile for the interim PCOD V5 model.

Skjellerup, P. *et al.* 2015. Marine mammals and underwater noise in relation to pile driving. Working Group 2014. Report to the Danish Energy Authority.

Van Der Meij, H., Kastelein, R., Van Eekelen, E. & Van Koningsveld, M. 2015. Faunaguard: A Scientific Method for Deterring Marine Fauna. *Terra et Aqua* 138: 17-24.

Verfuss, U.K., Sinclair, R.R. & Sparling, C.E. 2019. A review of noise abatement systems for offshore wind farm construction noise, and the potential for their application in Scottish waters. *Scottish Natural Heritage Research Report* No. 1070.