Chapter 3. Characterisation of the operational noise, generated by offshore wind farms in the Belgian part of the North Sea.

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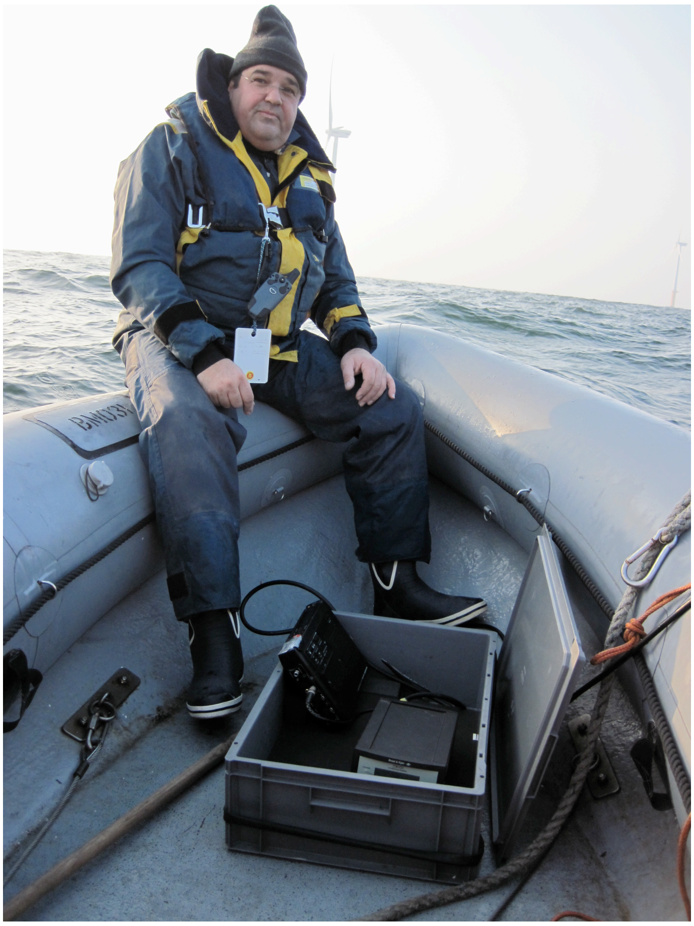

Underwater noise measurements on the Thorntonbank

Photo B. Rumes / RBINS / MUMM

Abstract

Offshore wind farms generate underwater noise during construction, operation and decommissioning. Underwater noise emitted by windmills in operational (production) mode needs to be quantified in order to better understand the full range of environmental impacts that wind energy production at sea may have on the surrounding marine life.

In this paper, operational underwater noise emitted by offshore wind farms in the Belgian part of the North Sea (BPNS) is quantified and compared to other locations in European Marine waters as well as the background situation prevailing before implementation. Measurements undertaken at two different offshore wind farms, one with 5 Megawatt (MW) turbines on concrete gravity based foundations (GBF) and one with 3 MW turbines on steel monopile foundations showed a different operational noise emission. The GBF offshore wind farm featured a slight increase of sound pressure level (SPL) of max 8 dB re 1μ Pa compared to ambient noise measured before construction. A more important SPL increase of 20 to 25 dB re 1μ Pa was observed for an offshore wind farm built using steel monopile foundations. Such noise emissions are much lower than those during piling in the construction phases. Nevertheless, this noise is being emitted during the operational phase of the wind farm, a period that is foreseen to last at least 20 years. As such, it is important to quantify the emissions in order to identify any possible impact.

Samenvatting

Een offshore windpark genereert onderwatergeluid tijdens de bouw-, operationele en ontmantelingsfase. Onderwatergeluid van windmolens in de operationele (productie)-modus moet worden gekwantificeerd om beter inzicht te verwerven in de gevolgen die de productie van windenergie op zee kan hebben op het omliggende mariene milieu.

In dit hoofdstuk is het operationeel onderwatergeluid afkomstig van offshore windparken gesitueerd in het Belgische deel van de Noordzee (BDNZ) gekwantificeerd en vergeleken met de resultaten uit andere parken in de Europese mariene wateren, alsook met de achtergrondsituatie voor de constructie van de windparken. Metingen uitgevoerd in twee verschillende offshore windparken, één waarbij men gebruik maakt van een gravitaire funderingen (gravity based foundation - GBF) en één met stalen monopile funderingen, wijzen op verschillende operationele geluidsemissies. In het offshore windpark met GBF werd een lichte stijging van het geluidsdrukniveau (Sound Pressure Level - SPL) waargenomen van max. 8 dB re 1μ Pa ten opzichte van omgevingsgeluid gemeten voor de bouw. Een belangrijkere verhoging in SPL van 20 tot 25 dB re 1μ Pa werd waargenomen in een offshore windpark waar stalen monopile funderingen worden gebruikt. Dergelijke geluidsemissies zijn veel lager dan tijdens de bouwfase, vooral indien de bouwfase het heien van palen vereist. Echter, operationele geluidsemissies vinden plaats tijdens de hele levensduur van het windpark (voorzien voor minstens 20 jaar) en daarom is het belangrijk om deze te kwantificeren om zo eventuele gevolgen te identificeren.

3.1. Introduction

According to the Marine Strategy Framework Directive (MSFD), EU Member States have to determine and control good environmental status (GES) for their marine waters (Tasker *et al*., 2010). One of the 13 descriptors of GES relates to anthropogenically induced underwater noise, as this may conflict with various ecosystem processes among which marine mammal communication (Richardson *et al.,* 1985; NRC, 2005; Nowacek *et al.,* 2007). Excessive underwater noise hence is considered a potential threat to the marine environment, receiving attention even at the European level. Human activities at sea indeed may generate underwater noise that could be harmful for marine life. Boyd *et al*. (2008) identified air guns, pile driving, intense low -or mid- frequency sonar, dredges, drills, bottom towed fishing gear, explosions, recreation vessels, acoustic deterrents, overflying aircraft (including sonic booms) and shipping as sources of anthropogenic noise that could affect marine mammals.

At present major attention is paid to the underwater noise and its ecological impacts generated by the construction, operation and in the future also dismantlement of offshore wind farms (Huddelston, 2010). When such underwater noise is considered, four different phases should be distinguished during the life cycle of an offshore wind farm: (1) before implantation - 'T reference' situation, (2) the construction phase, (3) the operational phase and (4) the dismantlement phase (Nedwell *et al.,* 2004). For the Belgian part of the North Sea (BPNS), several studies already documented the first two phases. The initial situation (T reference) at the Thorntonbank (C-Power site) was documented by Henriet *et al*. (2006), while Haelters *et al*. (2009) investigated the initial situation (T reference) at the Bligh Bank (Belwind site). Both T reference spectra are presented in Figure 2 and feature mean SPL just little above 100 dB re 1µ Pa for Thortonbank and just below 100 dB re 1µ Pa at the Bligh Bank. The construction phase was documented by Haelters *et al.* (2009) for six gravity-based founded (GBF) wind mills at the Thorntonbank and by Norro *et al*. (2010) for piling activities at the Bligh Bank. The spectrum measured 770 m away from the piling source is presented in Figure 2 and a peak SPL of 193 dB re 1 µPa was measured at that distance. The operational and – later on – dismantlement phases are yet to be quantified.

During the operational phase, underwater noise is produced by the rotation of the wind turbines and is transmitted to the water by the support structure. Operational underwater noise produces SPL much lower than that emitted during the construction phase, especially when pile-driving is applied (Huddleston, 2010). However, the construction noise generally lasts for a limited period of time (weeks to months), while operational noise is produced throughout the lifetime of the wind farm (more than 20 years) and may therefore have a chronic impact on the marine ecosystem.

Measurements of operational noise emitted by the Horns Rev and Nysted offshore wind farms for instance showed a higher than background noise intensity at a frequency below 1 kHz. Boesen & Kjaer (2005) provided that information without quantification. Betke (2006) further demonstrated the operational noise of a 2 MW turbine to have its highest sound pressure levels at about 150 Hz and 300 Hz, with a respective sound pressure level of 118 dB and 105 dB re 1 µPa. The operational noise also proved to depend on the type of foundation used (Uffe, 2002): concrete and steel pile foundations showed different spectral features such as a difference of 10 dB re 1µ Pa at 100 Hz and 15 dB re 1µ Pa at 200 Hz between the two types of foundations (steel foundation being noisier). That study further qualified the noise emitted by both types of foundation as stronger than the ambient noise for the frequencies below 1kHz (30dB re 1µ Pa at 100 Hz and 20 dB re 1µ Pa at 200 Hz). However, Nedwell *et al*. (2007) concluded that operational noise produced by windmills could fall well within the natural range of variability in background noise levels.

This paper presents the first data on operational underwater noise of both the C-Power and Belwind offshore wind farms and, as such, contributes to the characterisation of human induced underwater noise in the BPNS.

3.2. Material and Methods

3.2.1. Measurements methodology

The same measurement protocol as used for previous underwater noise measurements in Belgian wind farms was used for the present study. In summary: measurements of wind farm operational noise were performed from a drifting Rigid Hull Inflatable Boat (RHIB) inside the park in the vicinity of the windmills (Figure 1a & b). To avoid interaction with the hydrophone, the engine, radar and echosounder were turned off. The geographic position and time were recorded with a handheld GPS GARMIN GPSMap60 every 5 seconds. The clock of the recorder was synchronised beforehand with the GPS-time (UTC). At the start and the end of each measurement a reference signal was recorded. For more details: see Haelters *et al.* (2009).

Three recordings of 20 min each were made on the 8th of March 2010 at the Thorntonbank site, featuring concrete GBF foundations and on the 4th of March 2011 at the Bligh Bank site, featuring steel pile foundations. During the latter recording, a few small working boats were present in the area. Two recordings were well within the wind farm and as such truly measured operational noise (Figure 1), while one record was taken at great distance (+6 km) from the offshore wind farm and should hence be considered a background noise measurement. Weather conditions encountered on the 8th March 2010 and 4th March 2011 featured wind of 4-5 BF and a sea state of 2 to 3.

Table 1.
Geographic position and distance to the windmills of the selected recordings (coordinates in WGS84).

Selected recordings at the Thorntonbank (8th March 2010)					
Position start recording				**Distance from windmill (m)**	**Type of noise**
Northing		**Easting**			
51°	32.874’	2°	55.769’	12-520	Operational noise
51°	30.422’	2°	51.967’	6400-7200	Background
Selected recording at the Bligh Bank (4th March 2011)					
Position start recording				**Distance from windmill (m)**	
Northing		**Easting**			
51°	38.908’	2°	48.064’	186-1200	Operational noise

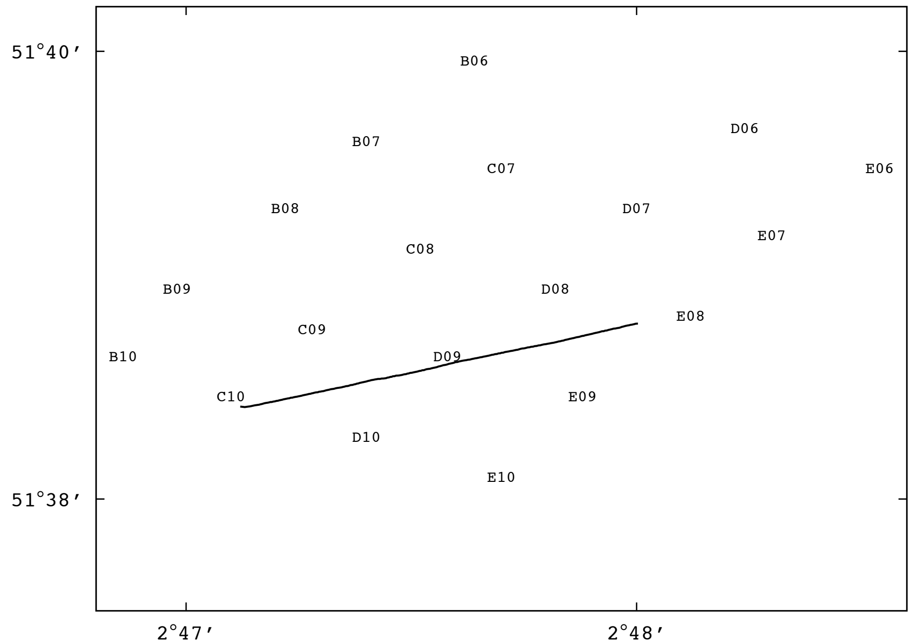

Figure 1a. Track path (black line), realised inside the Belwind (Bligh Bank) wind farm on the 4th April 2011. Steel monopile positions at the centre of the name label. Latitude North and Longitude East from Greenwich.

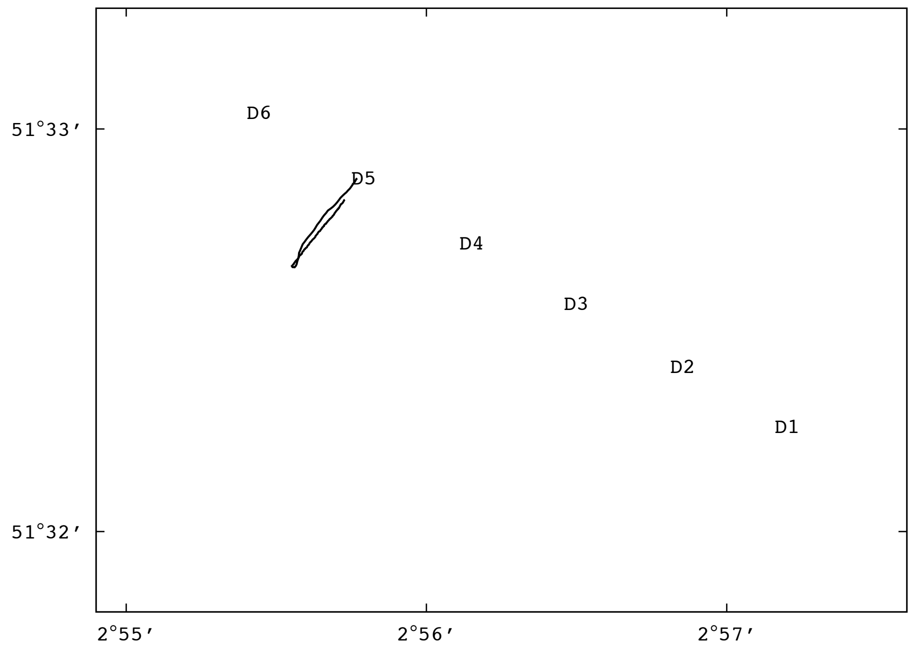

Figure 1b. Track path (black line), realised inside the C-Power (Thorntonbank) wind farm on the 8th March 2010. GBF positions at the centre of the name label. Latitude North and Longitude Est from Greenwich

3.2.2. Acoustic measurement equipment

At every measurement, one Brüel & Kjær hydrophone (type 8104) was deployed at a depth of 10 m. A Brüel & Kjær amplifier (Nexus type 2692-0S4) was connected between the hydrophone and the recorder in order to allow for an amplification of the signal. The reference signal was used together with the output sensitivity of the Nexus to calibrate the recorded signal. The signal was recorded using an audio MARANTZ Solid State Recorder (type PMD671). It was operated with the highest possible sampling rate of 44100 Hz. The signal was recorded in WAVE format (.wav) on Compact Flash cards of 2 GB (Sandisk Ultra II). Batteries powered all equipment.

3.2.3. Analysis of the recordings

Analysis here focused on the third octave band spectrum of the underwater SPL. The spectra were computed using MATLAB routines built according to the norm IEC1260. For reasons of comparison, the spectra of the three recordings (Belwind and C-Power in operation and the background noise at the C-Power site) were further complemented with former measurements of (1) the T reference noise at the Thorntonbank (Henriet *et al.*, 2006) and the Bligh Bank (Haelters *et al.*, 2009) and (2) the piling noise at the Bligh Bank (Norro *et al.,* 2010).

3.3. Results

The three spectra representing T reference, background and operational situation at the Thorntonbank all showed a similar amplitude all along the frequency domain (Figure 2). Some differences of 5 to 8 dB re 1 µPa were observed between the T reference noise (CP T_{ref}) and the two newly recorded spectra (CP Background and CP Operational) at the Thorntonbank. These differences were maximal at 110 and 200 Hz and at 4 kHz. At the Bligh Bank, an overall difference in SPL of about 20 dB re 1 µPa was observed between the reference measurement (BW T_{ref}) and operational noise (BW Operational). This difference in amplitude increased to 25 dB re 1 µPa at a frequency of 8 kHz. Except for the Belwind operational noise, all spectra decayed at frequencies higher than 1 kHz.

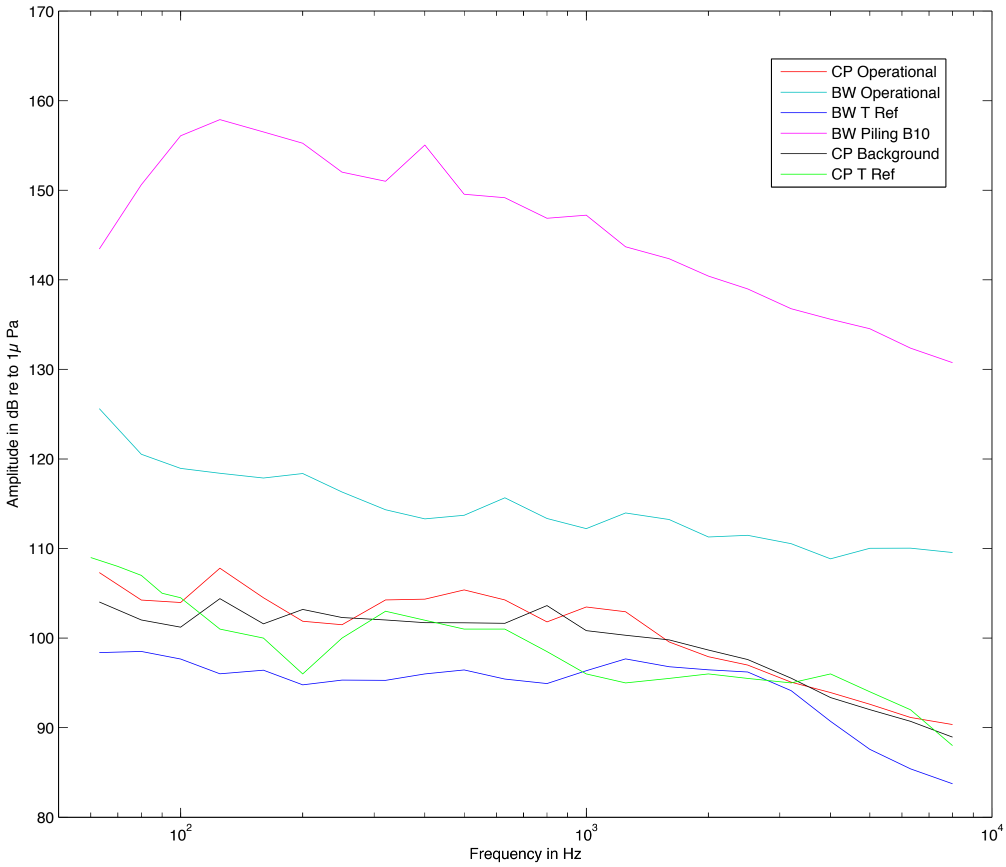

Figure 2. Spectra of underwater noise, measured inside the C-Power (CP) and Belwind (BW) wind farms, located respectively at the Thorntonbank and Bligh Bank. Operational noise generated during wind farm operation; T Reference (T ref), measurement before the construction activities started; background: measurement at > 6 km from the C-Power wind farm in operation; piling B10, spectra measured at 770 m from the piling activities at location B10.

All T reference and background spectra were at minimum 34 dB re 1 µPa below the piling spectrum (Figure 2). The operational noise, generated by the C-Power GBF windmills in operation was 52 dB re 1 µPa lower at 110 Hz, while this difference decreased to 39 dB re 1 µPa at 110 Hz for the operating Belwind steel monopile windmills.

The operational spectra of both wind farms showed clear SPL peaks at frequencies ranging from 100 Hz to 1 kHz (Figure 2). A first peak at about 130Hz was visible at the C-Power site, while the first peak visible within the operating Belwind wind farm was shifted to about 200 Hz. At higher frequencies, several peaks were observed at similar frequencies (i.e. 600 Hz and 1,3 kHz) for both wind farms. The absolute lowest SPL was recorded during the reference noise measurement at the Bligh Bank.

Finally, some differences in reference and background noise levels were observed within both offshore wind farms, with the Bligh Bank situation representing the most quiet condition.

3.4. Discussion

3.4.1. Operational noise versus T reference noise and importance of the foundation type

A difference of about 20 dB re 1 μPa was found between the Belwind T reference and operational noise. As different weather conditions could not explain such difference (see next §) the difference should be interpreted as true operational noise, produced by steel monopiles, as supported by the fact that the RHIB was inside the concession area throughout its complete drift (Figure 1a) and was passing close to the E08, D09 and C10 windmills. Furthermore, only a few small working boats were present in the direct vicinity of the hydrophone during measurement.

Compared to the T reference noise levels, the operational noise measurements at the C-Power wind farm (Figure 2) showed a slight increase from 5 to 8 dB re 1 μPa at e.g. 110 Hz, 200 Hz and at frequencies a little higher than 1 kHz, while the difference was neglectable at 60 Hz, 100 Hz, 320 Hz and 3,2 kHz. As such, the operational noise of the C-Power GBF windmills can be considered low. It should however be noted that the number of windmills, contributing to the recorded noise, was potentially (much) higher in the Belwind wind farm compared to the C-Power wind farm (Figures 1a, b), which might explain the increased SPL at the Belwind site. This effect might however have been counteracted by the fact that the recordings at the C-Power site started closest to the windmill. Although the differential effect of both issues cannot be evaluated for the time being, there is no basis to assume that these might have largely influenced our measurements.

We consequently demonstrated that concrete GBF windmills are likely to be less noisy (- 20dB re 1 μPa) than steel foundation windmills. We furthermore showed that, contrary to what was forecasted by Uffe (2002), the operation of steel pile foundation windmills is noisier than the natural ecosystem conditions over the frequency of 1 kHz (cf. reference noise levels). Steel pile foundation windmills finally lacked the decay of the spectrum at frequencies higher than 1 kHz, typical for the reference, background and operational GBF windmill noise as observed at the C-Power and Belwind wind farms.

Nedwell *et al.* (2007), Boesen C. & Kjaer J. (2005) and Betke (2006) all demonstrated that operational noise represent a light SPL increase of few dB re 1 μPa over the background levels. We observe a similar situation even if the turbines in the BPNS are more powerful with six 5 MW turbines at the C-Power site and 55 3 MW turbines at the Belwind site. The differences are situated on the higher SPL measured (20 to 25 dB re 1 μPa) for steel foundation as well as the decay of the spectrum over the frequency of 1kHz measured for steel foundation that is not present here but that Betke (2006) and Uffe (2002) proposed.

We have to remark however that the lack of standardization in underwater sound measurements and treatment complicates detailed comparison with other studies. Betke (2006) for example measured the operational noise at 100 m from the source or standardized the SPL to 100 m using a linear propagation model. Nedwell *et al.* (2007) on the other hand measured while drifting inside or outside the wind farm and presented noise spectra at various distances from a given windmill. Attempts to develop a necessary standardization are ongoing (de Jong *et al.*, 2010; Muller & Zerbs, 2011).

3.4.2. T reference and background noise levels are influenced by weather conditions and geographic position

The differences in reference and background noise levels could be partially attributed to the differences in weather conditions encountered during field work, and partially to the geographic position of both wind farms. The Belwind background noise was measured in very calm weather conditions (Haelters *et al.*, 2009). The C-Power background noise measurement was measured with moderately windy conditions (BF 4-5), whereas the C-Power reference condition was measured in very calm weather conditions (Henriet *et al.*, 2006). At least we can conclude that within the range of calm to moderate wind conditions and sea state, weather is not significantly impacting the measurement. The distance to a shipping traffic lane or the presence of pipelines in the area, as is the case for the C-Power site (Henriet *et al*., 2006), further explain the difference in T reference and background SPLs between C-Power and Belwind sites with Belwind being the less noisy site. One should however keep in mind that in the BPNS there is no place free of any anthropogenic activity. As such, disentangling the influence of the various sources of noise on the noise spectra remains impossible at this time.

3.4.3. Compliance with the EU MSFD descriptors

As the MSFD is yet to be fully implemented and applied in the EU Member States, a final operational definition of GES for Descriptor 11 "Underwater noise" is yet to set. Nevertheless, efforts to provide an overview of indicators and possible thresholds for GES are already undertaken. Tasker *et al*. (2010), for example, proposed for the continuous low frequency underwater noise an average sound pressure level of maximum 100 dB re 1 μPa for the octave band centred on 63 and 125 Hz. More recently, however, the identification of trends in SPL within the same two 1/3-octave bands rather than maximum values are proposed. A clear cut evaluation of whether or not the operational noise of Belgian offshore wind farms meet the MSFD criteria is hence not possible at present.

In the BPNS all operational noise measured so far is over the limit of 100 dB re 1 μPa. Moreover steel pile foundations equipped with a 3 MW generator (Bligh Bank) are some 20 dB re 1 μPa noisier in operation than GBF windmills equipped with a 5 MW generator. At this stage, the limited data available makes it impossible to detect a statistically significant trend. More noise recordings are advised in order to draw firm conclusions. A trend analysis based on the method developed in Norro *et al.* (2006) could be used in the future.

It is however expected that because of (1) the relatively low increase of underwater noise, generated by the GBF and steel pile wind mills, and (2) the relatively high natural variability in underwater noise, caused by e.g. varying position and possibly weather conditions, such operational noise of will not be qualified as intolerable.

3.4.4. Possible impact on the marine life

Betke (2006) concluded that the operational noise emitted by the Horns Rev wind farm cannot be noticed by a harbour porpoise (*Phocoena phocoena*) at a 100 m distance from the turbine, but that caution is needed because of the actual limited knowledge on this topic. Nedwell *et al.* (2007) stated that the slight increase in noise in the immediate vicinity of operating windmills is very unlikely to cause any behavioural response in seabass (*Dicentrarchus labrax*), cod (*Gadus morhua*), dab (*Limanda limanda*) herring (*Clupea harengus*), salmon (*Salmo salar*), bottlenose dolphin (*Tursiops truncatus*), harbour porpoise and common seal (*Phoca vitulina*). Ward *et al.* (2006) however indicated that bottlenose dolphins and harbour porpoises would be aware of the operational noise at a distance of 200 m from the North Hoyle Offshore wind farm, but concluded that the SPL (105 to 135 dB re 1 μPa at 100 Hz) could not cause any hearing damage.

Our data suggests that hearing damage to marine mammals should not be expected from the operational noise of offshore wind farms. Whether or not a 20 dB re 1 μPa increase of underwater SPL as observed for steel pile foundations may cause a behavioural response in marine mammals or other organisms remains an open question.

3.5. Conclusions and perspectives

The operational noise emitted by offshore wind farms in the BPNS showed an increase compared to T reference SPL. An increase of about 20 dB re 1 μPa for frequencies below 3 kHz and about 25 dB re 1 μPa at 8 kHz were observed for the Belwind offshore wind farm located at the Bligh Bank (consisting of 55 5 m diameter steel piles equipped with 3 MW turbines). The increase in SPL observed at the Thorntonbank was lower with a maximum of 8 dB re 1 μ Pa measured at the C-Power offshore wind farm (consisting of 6 concrete GBF equipped with 5 MW turbines). No data are available yet to confirm or infirm any effect such increase may have on the marine life on this zone of the BPNS.

3.6. Acknowledgements

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3.7. References

Betke, K., (2006). Measurement of underwater noise emitted by an offshore wind turbine at Horns Rev. ITAP report 13/02/2006. 19pp.

Boesen, C. & Kjaer, J., (2005). Review report 2004. The Danish Offshore Wind Farm Demonstration Project: Horns Rev and Nysted Offshore Wind Farms, Environmental impact assessment and monitoring. Elsam Engineering and ENERGI E2, 135 pp.

Boyd, I., Brownell, B., Cato, D., Clarke, C., Costa, D., Evans, P., Gedanke, J., Gentry, R., Gisner, B., Gordon, J., Jepson, P., Miller, P., Rendell, L., Tasker, M., Tyack, P., Vos, E., Whitehead, H., Wartzok, D. & Zimmer, W., (2008). The effects of anthropogenic sound on marine mammals. A draft research strategy. European Science Foundation Marine Board Position paper 13. 92 pp.

De Jong, C.A.F, Ainslie, M.A & Blacquière, G., (2010). Measuring Underwater Sound: Towards measurement standards and noise descriptors. TNO 2010. 45 pp and 5 annexes.

Haelters, J., Norro, A. & Jacques, T., (2009). Underwater noise emission during the phase I construction of the C-Power wind farm and baseline for the Belwind wind farm. *In:* Degraer, S. & Brabant, R. (Eds.) Offshore wind farms in the Belgian part of the North Sea. State of the art after two years of environmental monitoring. Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models. Marine ecosystem management unit. Chapter 3: 17-37.

Henriet, J.-P., Versteeg, W., Staelens, P., Vercruysse, J. & Van Rooij, D., (2006). Monitoring van het onderwatergeluid op de Thorntonbank: referentietoestand van het jaar nul, eindrapport. Studie in opdracht van het KBIN/BMM, rapport JPH/2005/sec15 , Renard Centre of Marine Geology Ghent University, Belgium July, 2006.

Huddelston, J., (ed) (2010). Understanding the environmental impacts of offshore windfarms COWRIE 138 pp.

Muller, A. & Zerbs, C., (2011). Offshore wind farms. Measurement instruction for waterborne sound measurements. Report N° M88 607/5. Muller-BBM GmbH. 21 pp.

Nedwell, J.R. & Howell, D., (2004). A review of offshore wind farm related underwater noise sources. Report N° 544 R 0308 COWRIE oct 2004. 57 pp.

Nedwell, J.R., Parvin, S.J., Edwards, B., Workman, R., Brooker, A.G. & Kynoch, J.E., (2007). Measurements and interpretation of underwater noise during construction and operation of offshore wind farms in UK waters. COWRIES- Subacoustech. NOISE 03-2003. 80pp.

Nowacek, D.P., Thorne, L.H., Johnston,D.W. & Tyack, P.L., (2007). Responses of cetaceans to anthropogenic noise. Mammal Rev, 37: 81-115.

Norro, A., Pichot, G., Pison, V. & J., Ozer, (2006). A bi-dimentional approach to assessing the volumetric evolution of an exploited sandbank. Ices Journal of Marine Science, 63:176-186.

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:* Degraer, S., Brabant, R., Rumes, B., (eds) (2010). Offshore wind farms in the Belgian part of the North Sea. Early environmental impact assessment and spatio-temporal variability. Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models. Marine ecosystem management unit. Chapter 4: 37-51.

NRC, (2005). National Research Concil. Marine Mammal Populations and Ocean Noise. Determining when noise causes biologically significant effects. The national academies press. Washington DC. 126 pp.

Richardson, W.J., Fraker, M.A., Wuersig, B. & Wells, R.S., (1985). Behaviour of bowhead whales, *Balaena mysiticetus* summering in the Baeufort sea/ reactions to industrial activities. Bilogical Cpnservation, 32:195 – 230.

Tasker, M.L., Amundin, M., Andre, M., Hawkins, A., Lang, B., Merck, T., Sholik-Scholmer, A., Teilmann, J., Thomsen, F., Werner, S. & Zakharia, M., (2010). Indicator for the good environmental status for underwater noise and other form of energy. The main report of task group 11 for Marine Strategy Framework Directive's descriptor 11 Draft 11:01/2010. 39pp ICES/JRC report.

Uffe, D., (2002). Measurements of noise induced from offshore wind turbines and ambient noise in the sea water. Giga Wind Hannover, Germany. 23 pp.

Ward, P.D., Harland, E. & Dovey, P., (2006). Measuring ambient noise in relation to offshore wind farm characterisation. QinetiQ 2006. 5 pp.