EXECUTIVE SUMMARY

EMPIRICAL EVIDENCE INSPIRING PRIORITY MONITORING, RESEARCH AND MANAGEMENT

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By the end of 2020, *i.e.* twelve years after the installation of the first wind turbines in the Belgian part of the North Sea, an installed capacity of 2.26 Gigawatts (GW), consisting of 394 offshore wind turbines and covering 238 km², will be operational in the Belgian part of the North Sea (chapter 1). They are expected to produce an average of 8 TWh annually, which is around 10% of the total national electricity demand or nearly 50% of the electricity needs of all Belgian households. Although no new projects are scheduled in the next years, long-term developments include an additional zone of 285 km² for a production capacity of ~2 GW of offshore wind energy which has been delineated in the new marine spatial plan. With 523 km² reserved and planned for offshore wind farms in Belgium, 344 km² in the adjacent Dutch Borssele zone, and 122 km² in the French Dunkerque zone, cumulative ecological impacts will undoubtedly continue to be a major concern in the years to come. We hence continue to be ever more faced with the challenge to optimise measures to combat the energy crisis in the light of combatting the biodiversity crisis. Tackling this challenge will necessitate the generation of new knowledge as well as a maximum uptake of existing and new knowledge to facilitate an environment-friendly management of offshore renewable energy developments, hence inspiring priority monitoring, research and management. This knowledge should cover a broad range of ecosystem components from soft sediment and (artificial) hard substrate invertebrates and fish to seabirds and marine mammals, as well as their interactions, all of which are impacted by offshore renewable energy developments in different ways.

Given the potential negative impact on the marine ecosystem, excessive sound levels are considered one of the main pressures during the construction phase of offshore wind farms; this particularly when pile driving is involved. Next to sound production, propagation and mitigation modelling, *in situ* measurements of piling events have received a lot of attention during the last decades, also in the Belgian part of the North Sea. After ten years of pile driving activities in Belgian waters, the last turbine foundation was hammered in the seafloor of the first offshore renewable energy zone on 2 January 2020. Until construction activities start in the second Belgian renewable energy zone, this was the last event of pile driving in Belgian waters. The last turbine foundations installed, consisting of extra-large steel monopiles with a diameter of 7.4 and 8 m, were piled using large hydraulic hammers of 3000 and 4000 kJ, respectively (chapter 2). The associated excessive sound levels were reduced using a double big bubble curtain (DBBC) mitigation technique for the first time in Belgian waters. A double bubble curtain is formed around a pile by freely rising bubbles created by compressed air injected into the water through two rings of perforated pipes encircling the pile. *In situ* measurements of underwater sound generated during 14 full pile driving events showed zero to peak sound levels ranging from 183 to 193 dB re 1 µ Pa when normalised to a distance of 750 m from the source. This represented an estimated zero to peak sound level reduction of 12-20 dB re 1 µPa. The variability in efficiency of sound level reduction may be explained by the technical set-up of the DBBC but also by environmental conditions like tidal currents which should receive extra attention while designing the DBBC as to optimise sound reduction. We further detected the efficiency of sound level reduction to be higher for frequencies above 300 Hz while mainly lower frequency sounds are emitted during pile driving.

Marine mammals are particularly at risk of being negatively impacted by the excessive sound levels produced during pile driving. Sound mitigation measures to reduce that impact are therefore outlined in the environmental license conditions. Initial license conditions were aimed at preventing near-field injury to individual animals and included the use of an acoustic deterrent device as well as a prohibition on starting pile driving if a marine mammal was observed in the vicinity of the construction zone (chapter 3). Progressive insight in the potential population consequences of far-field behavioural disturbance led to the formulation of further permit conditions. These included a seasonal pile driving ban from 1 January to 30 April, and an obligation to use noise mitigation measures that limit the transmission of noise pollution to the marine environment. The interim Population Consequences of Disturbance model (iPCOD), simulating how different approaches to sound mitigation during pile driving can impact a harbour porpoise *Phocoena phocoena* population over a period of 25 years, showed that the applied mitigation measures reduced the average porpoise population decline at the end of the offshore wind farm construction period by 50%, while the application of currently available measures would have reduced the population decline by 97%. Possible improvements to the environmental license conditions include optimising the use of acoustic deterrent devices, formalising obligatory marine mammal surveys, and requiring developers to comply with the national threshold for impulsive underwater sound. The associated direct cost (~0.5% of the construction cost of an average-sized offshore wind farm) and indirect costs (cf. no indication of an increased installation time) of the application of sound mitigation measures will not affect the overall economic viability of future projects.

Seabird collision risks need our continued attention, because the resulting additional mortality may have a substantial impact at the population level for long-lived seabird species with a delayed maturity and small clutch size. Despite the considerable uncertainty about the absolute number of seabird collisions, collision models do allow identifying which species face the highest collision risk and show great value in the collision risk analysis of different scenarios for offshore wind farm development. They hence offer a promising tool for strategic marine planning at both national and regional scale. We assessed the number of possible seabird collision victims for the fully developed first offshore renewable energy zone in the Belgian part of the North Sea based on the latest available knowledge on collision risk modelling (chapter 4). This was done for the six most abundant species, *i.e.* black-legged kittiwake *Rissa tridactyla*, lesser black-backed gull *Larus fuscus*, great black-backed gull *Larus marinus*, herring gull *Larus argentatus*, common gull *Larus canus* and northern gannet *Morus bassanus*. In total, 70 casualties per year (standard deviation: 53) are expected. This number may arise to 290 casualties (standard deviation: 205) depending on the source of the avoidance rates in the model, which still are heavily debated in the scientific community. With respectively 54% and 27% of the total number of collisions, the highest number of collisions are expected for greater and lesser black-backed gull, *Larus fuscus* and *Larus marinus*. With an increasing number of offshore wind farms built and planned in the North Sea, population level effects caused by additional mortality through collisions cannot be excluded and may conflict with seabird conservation goals. Our results demonstrate turbines with a larger distance between the sea surface and the lower tip of the rotor to result in lower collision risk and a high turbine density to result in a higher collision risk. This knowledge is of direct use for a seabird-friendly siting and design of future offshore wind farms.

Not all seabird species are equally at risk of colliding with the turbine blades. Twelve years of baseline monitoring of seabird displacement has revealed distinct patterns in the tendency of seabird species to either avoid or to be attracted to these OWFs. Striking parallels among wind farms were detected for some seabird species, while other species showed a substantial inconsistency in displacement among different wind farms. Because of limited insight in what is driving the variation in observed patterns, impact study results so far have had limited value in predicting expected displacement rates elsewhere. Increased knowledge on cause-effect relationships would strongly benefit future planning and impact assessments. The future monitoring focus should therefore be oriented towards more targeted research, aiming to an understanding of the actual impact of offshore wind farms on individual birds or bird populations, next to aspects supporting mitigation. The first Belgian offshore renewable energy zone been fully developed has now created a momentum to revisit the research strategy (chapter 5). Three future focus research themes were identified. First, we aim to perform more targeted analyses to look for a correlation between wind farm characteristics and locally observed displacement rates within the Belgian wind farm concession zone. Secondly, we will develop empirically informed species distribution models for northern gannet *Morus bassanus*, common guillemot *Uria aalge* and razorbill *Alca torda*. Together with prospects on wind energy developments and empirically-assessed displacement rates, the species-specific number of birds affected can be estimated, allowing for recommendations for mitigating and compensating measures in future marine spatial planning. Thirdly, we advise for tracking studies of lesser black-backed gull *Larus fuscus* to generate unprecedented knowledge on behavioural and foraging-related activities inside offshore wind farms. This will shed a light onto additional or decreased collision risk as a consequence of gull behaviour inside wind farms.

Impacts on the benthic communities are more subtle and cannot easily be classified as positive or negative. As part of the artificial reef effect, offshore wind turbines may for example impact the seafloor beyond their actual footprint. Locally modified water currents around turbine foundations, as well as the depositional flow of faecal pellets and other detrital material produced by suspension-feeding fouling organisms on the foundations, have earlier been suggested to contribute to a process of sediment fining and organic matter enrichment close to and in the wake of wind turbines; this with consequent shifts in macrobenthos community composition, diversity and abundance. An analysis of three years of soft sediment macrobenthos data in the vicinity of jacket foundations provided equivocal support for this (chapter 6). Seven to nine years after installation, sediments at 37.5 m from the jacket foundations indeed had a significantly higher proportion of fine sand compared to samples collected at further distance (350-500 m from the foundations). This was, however, only occasionally accompanied by a higher organic matter content. Although, average macrobenthos abundance and diversity were higher and higher nearby the turbines, these differences could not always be backed up statistically. Still, the macrobenthos community structure did consistently differ between nearby and distant locations. At nearby locations, macrobenthos significantly changed with time which was largely attributable to a decline in the abundance of the amphipod *Urothoe brevicornis* and the polychaetes *Spiophanes bombyx* and *Nephtys cirrosa*, typical for natural surroundings permeable sediments, and to an increase of several other species, in particular the sand mason *Lanice conchilega*, formerly unknown for this environment. This evolution is likely to increase the small-scale benthic heterogeneity because of positive feedback loops from the bio-engineering activity of *Lanice conchilega* aggregations on sediment fining and enrichment. Ideally, future basic monitoring need to better incorporate small-scale variability in its sampling design, whereas targeted monitoring efforts should be directed at determining the spatial extent over which fining and enrichment is manifesting.

Changes to the larger soft sediment epibenthos and demersal fish communities that reside on the soft sediments in between the turbines were equally expected. However, nine years after construction no drastic changes could be detected for two offshore wind farms (chapter 7). The epibenthos and demersal fish assemblages remained structured mainly by temporal variability due to local and large-scale changes in temperature and climate (*in casu* the North Atlantic Oscillation and Atlantic Multidecadal Oscillation indices), rather than by the potential small-scale effect of the offshore wind farms. Still, some secondary effects are seen, which may be interpreted as the first signs of a refugium effect and an expansion of the artificial reef effect, hinting towards a positive effect of offshore wind farms on the epibenthos and demersal fish community. The refugium effect is suggested by the increased fish densities of some common soft sediment-associated fish species like common dragonet *Callionymus lyra*, solenette *Buglossidium luteum*, lesser weever *Echiichthys vipera* and plaice *Pleuronectes platessa* in one of two studied wind farms. This effect may result from fisheries exclusion combined with increased food availability. An expansion of the artificial reef effect is suggested through the appearance of an increased number of hard substrate-associated species, *e.g.* long-clawed porcelain crab *Pisidia longicornis*, edible crab *Cancer pagurus* and seabass *Dicentrarchus labrax* on the soft sediments. Increased densities of common squid *Loligo vulgaris* in one wind farm consisting of jacket foundation wind turbines could be an indication that cephalopods use the jacket foundations as substrate for egg deposition. However, the clearest indication for the artificial reef effect expansion was the increased abundances of blue mussel *Mytilus edulis* and anemones on the soft sediments in between the piles (> 200 m), two taxa dominating the epifouling communities on the turbines. Although mussel densities were still low (max. ~15 ind./1000 m^2), they may contribute to a future increased soft bottom habitat heterogeneity. Future monitoring is expected to demonstrate a continued heterogenisation of the soft sediment habitat with local biodiversity hotspots linked to patchy mussel drop offs.

Offshore wind turbine foundations indeed are heavily colonised by fouling organisms that mainly consist of suspension feeding invertebrates influencing local food web properties with possible knock-on effects at the wider spatial scale (chapter 8). A higher food web complexity was observed for the communities occurring in deeper parts of the turbines and in zones where organic matter accumulates (surrounding soft sediments and scour protection layer) compared to the upper parts of the foundation. The high trophic diversity and low redundancy in the soft sediment, scour protection layers and the *Metridium* zone on the foundation further suggest resources partitioning among and within the communities inhabiting these zones. The hard substrate species had larger trophic niches, exploiting a wider range of food sources, which allows for the co-existence of a multitude of species and a wide distribution of fouling organisms within and across depth zones. Two of the most common species, *i.e.* the amphipod *Jassa herdmani* and the mussel *Mytilus edulis* play a key role in the carbon assimilation process: we estimated that these two species' populations in the whole offshore renewable energy zone graze ~1.3% of the total annual local primary production of the Belgian part of the North Sea. While negligible relative to the primary production quantity, the consequent local deposition of organic matter likely has a considerable local effect on the sedimentary habitat and may indirectly influence the wider marine food web. The locally increased carbon assimilation (linked to secondary production) on its turn locally was shown to support higher trophic levels, demonstrated by benthic and bentho-pelagic species like sculpin *Myoxocephalus scorpioides*, cod *Gadus morhua* and pouting *Trisopterus luscus*, utilising the offshore wind farms as feeding grounds for longer periods. Even though these findings support the production hypothesis, further research is needed to prove that the locally increased secondary production of fish also has positive knock-on effects at the fish population level.