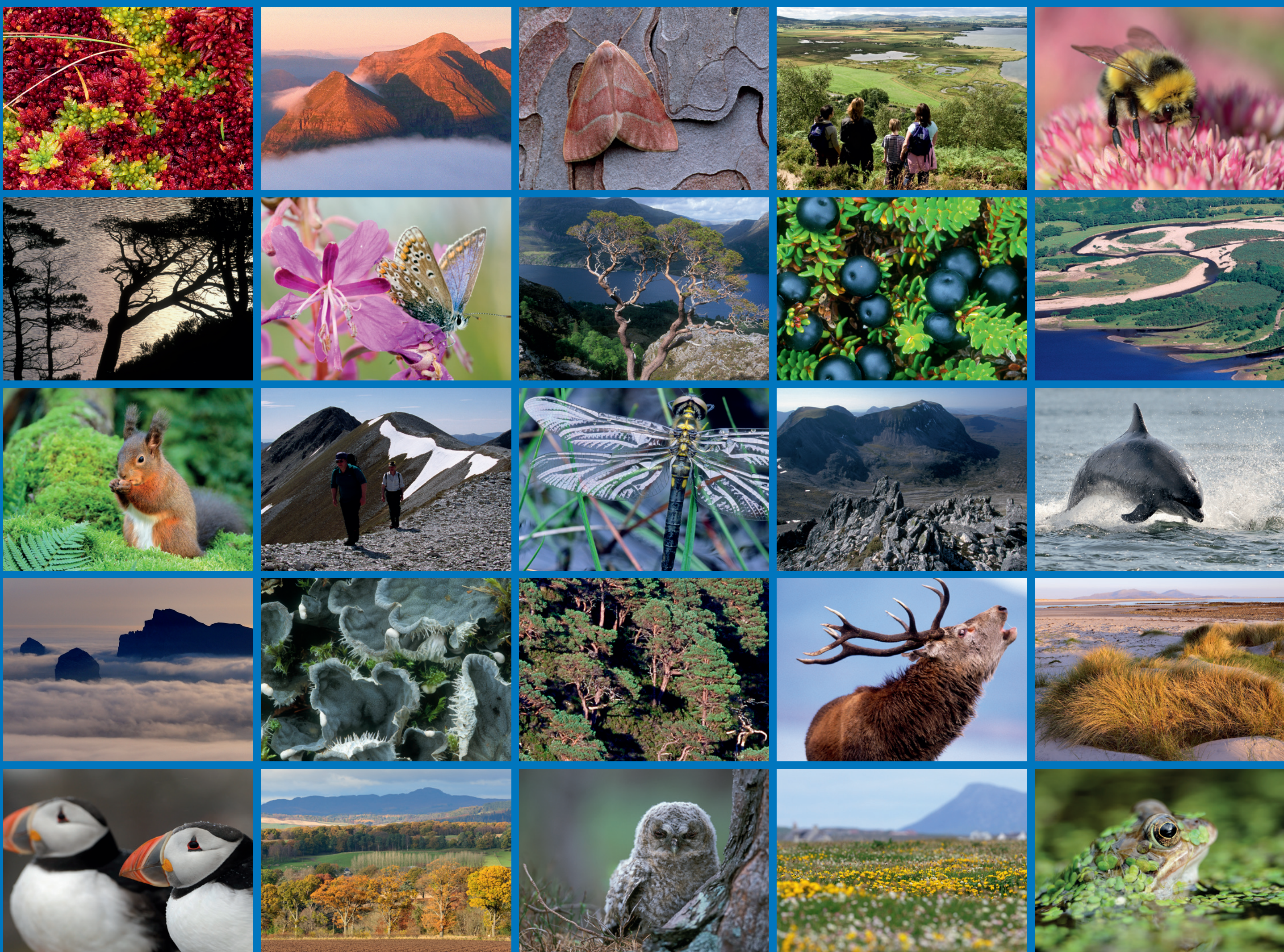
Scottish Natural Heritage
Research Report No. 1070

A review of noise abatement systems for offshore wind farm construction noise, and the potential for their application in Scottish waters



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RESEARCH REPORT

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A review of noise abatement systems for offshore wind farm construction noise, and the potential for their application in Scottish waters

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RESEARCH REPORT

Summary

A review of noise abatement systems for offshore wind farm construction noise, and the potential for their application in Scottish waters

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Project No: 017224
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Keywords

Marine mammals; fish; offshore wind farm; noise impact; Scotland; noise abatement methods; noise reduction; underwater noise; mitigation

Background

The Scottish Government supports plans to develop a large number of offshore wind farms (OWF) in Scottish territorial waters and the exclusive economic zone. The installation of foundations for offshore wind turbines often involves pile driving operations using large hydraulic hammers which introduce significant noise into the marine environment. Piling noise has the potential to impact both marine mammals and fish.

The primary objectives of this study were to undertake a review of available underwater noise abatement systems (NAS) in relation to their applicability for pile-driving operations for OWF construction in Scottish waters. Parameters of interest were: efficacy in noise reduction and the resulting benefit to marine fauna, practicality of use, cost, and impact/influence on the construction schedule. A secondary objective was to consider the applicability of existing NAS to mitigate noise generated by controlled explosions of unexploded ordnance. The study was based on a review of peer-reviewed publications and relevant ‘grey’ literature, combined with a questionnaire-based survey followed up by interviews with system-suppliers and end-users of NAS.

This review reflects available information, together with the knowledge, experience and opinions of NAS-suppliers and NAS-users, and does not necessarily reflect those of the authors or of Scottish Natural Heritage. This is not a detailed evaluation of which system can or cannot be deployed in specific wind farm areas.

Main findings

- Big Bubble Curtains (BBC), the IHC Noise Mitigation System (NMS), the Hydrosound damper (HSD) and vibrohammers (VH) have all been commercially deployed as NAS in OWF-projects.
- The AdBm-Noise Abatement System (AdBm-NAS) completed its full-scale test in 2018 and will be deployed commercially in an OWF-project in 2019.

- Currently under development are BLUE Piling Technology (BLUE Hammer) and HydroNAS.
- With the BBC, NMS and HSD, broadband sound levels can be reduced by at least 10 dB and reductions of up to 20 dB have been demonstrated, and more when combining two NAS.
- The VH emits continuous low-level noise that may need further assessment to ensure that this method indeed reduces impact on marine animals.
- The NAS are generally more effective at reducing the risk of noise impact on marine mammals and fish sensitive to higher frequencies than on fish that are only sensitive to frequencies below 100 Hz.
- BBC and VH are two NAS that have so far been applied in industrial projects in water depths prevailing in potential future Scottish OWF-sites (up to 77 m).
- BBC, VH, HSD and NMS are NAS that have been commercially deployed in OWF-projects in water depths up to 45 m.
- BBC and VH have been used with monopiles and jacket foundations, while NMS and HSD have only been used with monopiles, except for one HSD-prototype test with jacket foundations.
- Field experience with the deployment of all NAS in OWF-projects at water depth beyond ~45 m is lacking, however, most NAS are applicable in theory, although the application of the systems in deeper water may be challenging.
- Field experience with the deployment of NAS during the installation of piles with a diameter greater than ~8 m is lacking.
- The systems BLUE Hammer and AdBm-NAS have undergone full-scale tests, and the results should be publicly available in 2019. There is a lack of demonstrated commercial and serial deployment with these systems. The HydroNAS system has not undergone full-scale test and serial- and commercial deployment.
- Full knowledge on the drivability and bearing capacity of piles driven with BLUE Hammer is still lacking.
- There are perceived risks regarding drivability of piles using VH due to limited experience with the use of VH in OWF-projects.
- There are diverging opinions regarding the need to assess the axial bearing capacity of monopiles driven with VH.
- Filling these knowledge gaps will lead to a better understanding of the applicability of the NAS systems in Scottish waters.
- Project-specific assessment should be conducted to ensure the most suitable NAS option and configuration is chosen, if required, taking into account the environmental conditions of the OWF-site, and the specification of the installation vessel.
- Only the BBC has been proven to reduce the impact ranges caused by explosions during UXO-clearance, and, although there is one example of a BBC being applied during UXO clearance in water depths up to 90 m, its effectiveness has only been investigated in water depths up to 30 m.
- AdBm-NAS and HSD are potentially useful options for UXO-mitigation but this would need further investigations.

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Acknowledgements

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[1] completed questionnaire based on previous experience with offshore wind farm construction in Germany

1. GLOSSARY OF TERMS, ACRONYMS AND ABBREVIATIONS

Term	Description
AdBm-NAS	AdBm Noise Abatement System
BBC	Big Bubble Curtain
BfN	German Federal Agency for Nature Conservation
BLUE Hammer	BLUE Piling Technology
BSH	Federal Maritime and Hydrographic Agency of Germany
CES	Crown Estate Scotland
DBBC	Double Big Bubble Curtain
EEZ	Economic Exclusive Zone
ESRa	Evaluation von Systemen zur Rammschallminderung an einem Offshore-Testpfahl (research and development project)
GROW	Growth through Research, development & demonstration in Offshore Wind
H_s	Significant wave height
HF	High =-frequency
HSD	Hydro Sound Damper
HSE	Health, Safety and Environment
HydroNAS	HydroNAS™
$L_{pk,\ flat}$	Zero-to-Peak Sound Pressure Level, unweighted (= Peak sound pressure level)
LF	Low-frequency
MF	Mid-frequency
MW	MegaWatt
N/A	Not Applicable
NAS	Noise Abatement System
NMS	IHC Noise Mitigation Screen
OWA	Offshore Wind Accelerator
OWF	Offshore Wind Farm
PTS	Permanent threshold shift
PW	Phocid pinnipeds underwater
RAMS	Risk Assessments and Method Statements
RD&D	Research, Development and Demonstration
SBC	Single Bubble Curtain
SEL	Sound Exposure Level
SEL_{cum}	Cumulated Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SNH	Scottish Natural Heritage
tbd	To be determined
TCE	The Crown Estate
TRL	Technology Readiness Level
TTS	Temporary Threshold Shift
UXO	Unexploded ordnance
VH	Vibratory Hammer

2. NON-TECHNICAL SUMMARY

The Scottish Government supports plans to develop a large number of offshore wind farms (OWF) in Scottish territorial waters and the exclusive economic zone (EEZ). The installation of foundations for offshore wind turbines often involves pile driving operations using large hydraulic hammers which introduce significant noise into the marine environment. Piling noise has the potential to impact both marine mammals and fish.

The primary objectives of this study were to undertake a review of available underwater noise abatement systems (NAS) in relation to their applicability for pile-driving operations for OWF construction in Scottish waters. Parameters of interest were the efficacy in noise reduction, the benefit to marine fauna, practicality of use, cost, and impact/influence on the construction schedule. A secondary objective was to consider the relative applicability of the existing noise abatement technologies to mitigate noise generated by controlled explosions of unexploded ordnance.

To meet the primary objectives, technical, environmental and species-specific factors were considered to help understand:

- The scope of application, i.e., in which situations the NAS can be applied,
- The logistical requirements and limitations for the deployment and operation of the NAS to understand the associated cost implications,
- The environmental limitations that may influence the deployment and operation of NAS to link the suitability of the systems to the environmental conditions typical of the potential Scottish OWF sites,
- The direct cost implications associated with the use of NAS, and
- The noise reduction efficacy, i.e., how environmental and technical factors influence the efficacy, and for which target species the NAS might be most suitable.

The study was based on a review of published peer-reviewed and relevant 'grey' literature, combined with a questionnaire-based survey followed up by interviews with system-suppliers and end-users of NAS. The questionnaire that was sent to NAS-suppliers and users with targeted questions can be found in Annex 1.

The NAS considered were:

- Bubble curtains
    - Big Bubble Curtain (BBC) (two suppliers)
- Casings
    - Noise Mitigation Screen (NMS)
    - HydroNAS™ (HydroNAS)
- Resonators
    - Hydrosound damper (HSD),
    - AdBm Noise Abatement System (AdBm-NAS)
- Hammers other than impact pile-drivers
    - BLUE Piling Technology (BLUE Hammer)
    - Vibratory hammer (VH) (two suppliers)

The BBC, the NMS and the HSD have frequently been used for mitigating sound during OWF construction (installation of monopiles (BBC, NMS and HSD) and jacket foundations (BBC only)) in German waters and are considered by German authorities as state-of-the-art systems for water depths up to 40 m. All three systems provide a sound barrier around the piling position. With a BBC, a curtain consisting of a nozzle hose releasing ascending air bubbles is laid with a radius of tens to hundreds of meters around the piling position. The

NMS and the HSD enclose the pile at close distance, either with a sound insulating double-walled steel casing (NMS), or with a net of sound-absorbing foam elements (HSD).

The AdBm-NAS and the HydroNAS surround a foundation during piling activity with sound absorbing or reflective material. While the AdBm-NAS was recently tested in full-scale and will be applied commercially in an OWF-project in 2019, the HydroNAS is lacking a full-scale test but may be promising for future application. The BLUE Hammer, an impact hammer with less noise emission compared to a conventional hydraulic hammer, is also a promising system that has undergone its first full-scale test and will be improved based on the test results. VHs have been used at several OWFs, and work by driving the pile by vibration into the seabed rather than hammering it.

Most NAS considered in this review can be used for piling activities with the hammer operated either above the water or below the water surface. All systems are suitable for monopile installation and most of the systems can also be used for pin-pile installation.

Based on the information gathered in this review, some of the NAS may potentially be suitable for use at future Scottish OWF sites and will reduce noise emissions and therefore, potentially reduce impacts on marine mammals and fish. However, operational experience for OWF construction in water depths deeper than 45 m and with piles of a diameter greater than 8 m is lacking. With the current state-of-the-art NAS (BBC, NMS and HSD), broadband single strike sound exposure and peak levels can be reduced by at least 10 dB. The HSD seems to be less effective at reducing noise emissions than the NMS, and the effectiveness of a BBC depends on its configuration and deployment depth.

The most promising, currently available systems for Scottish OWF sites are the BBC and the HSD. A new model of the NMS would need to be built to ensure that is suitable for use in the deeper waters (> 50 m) of Scotland, and the BLUE Hammer is not yet commercially available. The efficacy of AdBm-NAS and HydroNAS have not yet been demonstrated in full-scale tests (although for the AdBm-NAS, these data should become available in 2019). The VH is commercially available and applicable in the environmental conditions prevailing in Scottish waters, however, the different kind of noise emissions produced during vibro-piling may need an appropriate impact assessment to ensure that this method does indeed reduce the impact on marine animals compared to conventional impact hammer piling methods.

Direct costs of applying a NAS start below € 5m for an 80 turbine OWF-project. However, direct costs increase with increasing environmental challenges at the project site and with increasing demands on the NAS effectiveness. Indirect costs also need to be considered, which may occur due to prolonged installation schedules and delays during foundation installation resulting from the use of NAS. The BLUE Hammer may be a promising future option, as it would replace the conventional hammer and thereby balance these costs. This may also be a future option for the VH however; the application currently needs to be combined with the use of a conventional hammer due to uncertainties with the bearing capacity (a measure of the stability of an installed pile) and drivability (the ability to install a pile dependent on the soil conditions). Therefore, the rental costs for both hammers need to be considered at present.

Due to the experience gained in German waters throughout the past decade, BBC, NMS and HSD have a proven record of applicability and efficacy for OWF-projects in water depths up to 45 m. The lack of experience in waters deeper than 45 m may bring challenges that have not yet been faced by NAS-suppliers and users. Time delays may occur in seasons and areas in which the weather conditions are unfavourable. The application of BBCs in areas with strong currents might also be challenging, especially in deeper waters.

Only the BBC and VH have been applied in commercial projects in water depths prevailing in future Scottish OWF sites, i.e., deeper than 45 m, however, these were not OWF-projects. No evaluation of the effectiveness of the BBC in these non-OWF-projects is available, and for the VH, a more detailed evaluation would need to be conducted to understand if the application of the VH in these projects is comparable to the applications in OWF-projects.

The efficacy of a NAS to reduce the likelihood of an animal to experience auditory injury depends on the frequency range at which sound energy is reduced and on the target species, as each species is sensitive to a certain frequency range. The NAS that have been proven at full-scale (BBC, HSD, NMS and BLUE Hammer) can reduce the sound exposure level of a single strike at 50 Hz by 6 to 7 dB, which is the frequency fish and low frequency (LF) cetaceans are particularly sensitive to. The efficacy increases with increasing frequency, which makes the systems suitable for all marine mammals and fish sensitive to higher frequencies. The NMS and BBC are most effective at higher frequencies (e.g., 10 kHz), which makes these systems especially effective in reducing impacts to high frequency cetaceans, such as the harbour porpoise. The HSD and AdBm-NAS may, in theory, be tuneable to reduce noise in specific frequency ranges and may therefore be tailored to the specific needs of a target species.

While mitigating noise impact, some NAS induce other impacts; for example, compressors are required for BBCs, which also produce noise (mainly airborne) and consume fuel, and an extra vessel is also required. The effectiveness of an HSD fatigues after several applications and needs to be replaced (and recycled by the supplier).

Based on the information retrieved through this review, the following knowledge gaps and uncertainties were revealed:

- Lack of experience with commercial deployment of NAS in OWF-projects in waters deeper than 45 m,
- Lack of field experience with NAS other than BBC and VH in waters deeper than 45 m,
- Lack of field experience with NAS for piles with a diameter greater than ~8 m
- Lack of field experience with NMS and little experience with HSD applied during the installation of jacket foundations,
- Lack of experience with serial and commercial deployment of BLUE Hammer and AdBm-NAS in OWF-projects, and outcomes of full-scale tests not yet published,
- Lack of full-scale tests with HydroNAS followed by serial and commercial deployment,
- Lack of noise impact assessment for VH,
- Perceived risks regarding drivability of piles installed with VH due to limited experience with the use of VH in OWF-projects,
- Diverging opinions regarding the need to assess the axial bearing capacity of monopiles driven with VH,
- Lack of full knowledge on drivability and bearing capacity of piles driven with BLUE Hammer.

Filling these gaps and reducing the uncertainties will lead to a better understanding of the applicability of the NAS in Scottish waters. Assessment of the feasibility of NAS would be required on a project specific basis to ensure that individual site and project characteristics are taken into account.

3. INTRODUCTION

3.1 Background

The Scottish Government has set ambitious targets for renewable energy generation. Renewable sources are expected to generate the equivalent of 100% of Scotland's gross annual electricity consumption by 2020[2]. In the future renewable energy mix, offshore wind energy is expected to play a major role. The Scottish Government is therefore supporting plans to develop several offshore wind farms (OWF) in Scottish territorial waters and the exclusive economic zone (EEZ). Further details can be found in Scotland's Offshore Wind Route Map[3].

The installation of foundations for offshore wind turbines often involves pile driving operations using large hydraulic hammers which introduce significant noise into the marine environment. Piling noise has the potential to impact the behaviour of marine mammals and fish (Popper *et al*., 2014, Southall *et al*., 2007) and may lead to auditory injury (National Marine Fisheries Service, 2018, Popper *et al*., 2014). Broad scale long-term noise impacts can potentially lead to population level effects (King *et al*., 2015, Verfuss *et al*., 2016a, Heinis *et al*., 2015).

Mitigation measures to reduce the risk of potential noise impacts during OWF construction have been applied in several European countries (Verfuss *et al*., 2016b). These measures are aimed at:

- Ensuring that no marine mammal is present within the potential impact zone around the piling position (by conducting marine mammal monitoring and/or using acoustic deterrent devices), or
- Protecting marine mammals during sensitive times and/or in sensitive habitats (by temporal or spatial piling restrictions), or
- Restricting the amount of noise energy emitted into the sea (by setting noise-thresholds) (Verfuss *et al*., 2016b).

To date, noise reduction measures have been required to meet specific noise thresholds (e.g., in Germany). These measures rely on the use of so-called *primary* and/or *secondary* noise mitigation methods (Bellmann *et al*., 2018). *Primary* noise mitigation methods aim to reduce noise emission at the source. This can be achieved through modifications of the piling process (e.g., adjusting the piling energy, or by the use of alternative hammer technologies (e.g., vibratory hammers, BLUE piling technology). Also the use of low noise foundations, such as suction buckets, gravity base foundations and floating substructures will avoid high noise emissions *a priori*. *Secondary* noise mitigation methods aim to reduce the noise propagated through the water column during pile driving. This may be achieved by the use of Noise Abatement Systems (NAS) such as casings, resonators or bubble curtains.

The efficacy of NAS in reducing the impact of piling noise on marine life depends on the species under consideration (the target species), the quantitative reduction in sound energy and qualitative changes to the sound signal. Short sound pulses with a sharp onset and high peak sound pressure (impulsive sound), as generated by conventional impact pile-drivers, are generally more harmful to marine life with regard to eliciting auditory injury compared to non-impulsive sounds. The risk and magnitude of auditory injury also increases with the increasing amount of energy an animal is exposed to. When considering fish, those with an anatomy that involves the swim bladder in hearing (particularly those with a connection between the inner ear and the swim bladder) are more sensitive to pile driving sound than

[2] https://www2.gov.scot/Topics/Business-Industry/Energy/Energy-sources/19185/17612
[3] https://www2.gov.scot/Publications/2013/01/5856

other fish types or their eggs and larvae (Popper *et al*., 2014). The degree of impact depends on the hearing range of the target species, which some guidelines consider for the assessment of auditory injury in marine mammals (e.g., National Marine Fisheries Service, 2018). It may also be important to consider the hearing range of the target species when determining the potential and magnitude of noise impact on animal behaviour (Tougaard *et al*., 2015). A reduction of sound energy in the lower frequency range reduces the impact on species groups with low frequency hearing such as baleen whales and harbour seals, while a reduction of sound energy in the higher frequency range will be effective for species groups with high frequency hearing such as the harbour porpoise. This means that some NAS are more effective for one species group than for another, depending on the frequency range at which noise energy will be reduced compared to the unmitigated noise.

The efficacy and applicability of NAS will depend on technical and operational limitations with regard to a number of factors including, but not limited to:

- Site specific parameters (water depths, soil properties),
- The metocean conditions (wind speed, wave heights, availability of weather windows, tidal and local current regimes),
- Size of the structures to be installed,
- Available crane capacities and deck space on the installation vessel (where there is not a requirement for a separate vessel), and
- The homogeneity of the bathymetry across a windfarm planning zone (Thomsen and Verfuss, in press).

This review has been commissioned by Scottish Natural Heritage (SNH) to provide information as to the current feasibility of NAS in Scottish waters.

This review reflects available information, together with the knowledge, experience and opinions of NAS-suppliers and NAS-users, and does not necessarily reflect those of the authors or of Scottish Natural Heritage. This is not a detailed evaluation of which system can or cannot be deployed in specific wind farm areas.

3.2 Objectives

The primary objectives of this study were to undertake a review of available underwater NAS with reference to their potential use in pile-driving operations in OWF construction in Scottish waters. Parameters of interest were the efficacy in noise reduction, the benefit to marine fauna, practicality of use, cost, and impact/influence on the construction schedule. This review outlines the current status of and experience with NAS for a better understanding of which systems may or may not have the potential to be deployed in Scottish waters, and which factors need to be considered to understand their applicability. An outcome of the review is the identification of further steps required to fill emerging knowledge gaps.

A secondary objective was to consider the usefulness of the existing noise abatement technologies to mitigate noise generated by controlled explosions of unexploded ordnance (UXO).

3.3 Approach and outline

The study was based on a review of published peer-reviewed and relevant ‘grey’ literature, combined with a questionnaire-based survey and interviews of system-suppliers and end-users of NAS. The questionnaire sent to NAS-suppliers and users with targeted questions can be found in Annex 1. The study was guided and reviewed by an independent expert panel, consisting of the following members: Dr Maria Boethling, Federal Maritime and Hydrographic Agency of Germany (BSH), Thomas Merck and Dr Alexander Liebschner, German Federal Agency for Nature Conservation (BfN) and Sven Koschinski (Meereszoologie, on behalf of BfN).

Section 4 presents a short overview of the development and deployment of NAS to identify the most suitable NAS for the reduction in noise emissions during impact pile-driving. The review is focused on European OWF projects in the North and Baltic Seas where the development of NAS has been most advanced in recent years.

Section 5 presents the NAS technologies considered in this review based on the initial literature review. The individual systems were evaluated in further detail with the help of the questionnaire-based survey and interviews.

Section 6 details the factors considered in the review of the NAS, including technical and logistical factors, environmental factors limiting the applicability and/or efficacy of the NAS, and species-specific factors that affect the effectiveness in reducing impact of any NAS applied.

Section 7 presents the offshore areas in Scottish waters considered for OWF construction at which the installation of piled foundations is planned or likely, and outlines the prevailing environmental conditions at these sites.

Section 8 presents the results of the survey, details the scope of the NAS application, the logistical requirements for the application of the NAS, the limitations during deployment and operation of NAS, the cost implications related to the use of NAS, and the noise reduction efficacy of the NAS.

Section 9 presents a high-level cost/benefit review of the systems.

Section 10 presents a review of the suitability of NAS for the mitigation of noise during controlled explosions of UXO.

Concluding remarks and recommendations are provided in sections 11 and 12.

4. DEVELOPMENT AND DEPLOYMENT OF NOISE ABATEMENT SYSTEMS

NAS have been considered as potential solutions for mitigating the impact of piling noise on marine mammals for more than two decades (e.g., during the Hong-Kong airport construction in 1996 (Würsig *et al*., 2000)). However, a review of NAS conducted around a decade ago by Nehls *et al*. (2007) revealed that no “off-the-shelf” NAS was available at the time of the review. In 2008, threshold criteria for underwater noise became effective in Germany (BSH, 2008, BSH, 2010, Thomsen and Verfuss, in press). This triggered the testing and development of NAS in order to mitigate piling noise during OWF construction to enable these thresholds to be met. Noise thresholds have also been implemented in other European countries, such as Belgium, Denmark and the Netherlands (Andersson *et al*., 2017, Thomsen and Verfuss, in press). Koschinski and Lüdemann (2013) provide a comprehensive review of NAS and other noise abatement methods that have been proposed and tested to comply with the mandatory noise thresholds in the German EEZ.

The research and development project “Evaluation von Systemen zur Rammschallminderung an einem Offshore-Testpfahl” (ESRa), tested the handling and efficacy of five different NAS in the Bay of Lübeck in the German part of the Baltic Sea (Wilke *et al*., 2012). Two of the systems involved in that project, along with a third system, are now considered by German authorities as “state-of-the-art” for water depths up to 40 m (Boethling, pers. comm.), i.e., they enable a sufficient reduction of the piling noise levels at these water depths to comply with the mandatory noise thresholds: The three systems are the Big Bubble Curtain (BBC), the Noise Mitigation Screen (NMS) and the Hydro Sound Damper (HSD). All three systems build a sound barrier around the piling position which reduces the sound levels that propagate beyond the barrier and are thus considered secondary noise mitigation methods. A more detailed description of these systems is provided in section 5.

The first full-scale test of a BBC during OWF construction was conducted in June 2008 at the FINO 3 research platform (Verfuss, 2014). In winter 2011/2012, an improved version of the BBC was then commercially deployed during the installation of 40 tripod foundations at the Borkum West II OWF in the German part of the North Sea (Diederichs *et al*., 2014). Prototypes of the NMS and HSD were included in the ESRa-project (Wilke *et al*., 2012). A prototype NMS was also tested during the installation of two monopile foundations for meteorological masts for the OWFs Ijmuiden Buiten in Belgium and Nordsee Ost in Germany, before it was used in 2012 for the installation of 30 monopile foundations at the OWF Riffgat in the German part of the North Sea[4]. In the same year, the HSD was tested in full-scale at one foundation at the London Array OWF in UK waters (Remmers and Bellmann, 2013), followed by a serial application of an improved HSD at the Amrumbank West OWF in German waters in 2013/2014 (Thomsen and Verfuss, in press). Until recently, these systems have been applied in a variety of OWF, mainly in German waters (Table 1, Philipp, 2018), but also in other European countries (e.g., BBCs were used at the OWFs Horns Rev III in Denmark[5] and Rentel OWF in Belgium (Degraer *et al*., 2018)). The BBC is the most commonly applied system for the mitigation of noise during turbine installation. The NMS and HSD systems have also been applied quite frequently (Table 2, Thomsen and Verfuss, in press).

[4] http://flow-offshore.nl/page/under-water-noise-mitigation-during-pile-driving-design
[5] https://www.offshorewind.biz/2017/10/20/first-monopiles-in-at-horns-rev-3/

Table 1. List of Offshore Wind Farms constructed in the German EEZ between 2011 and 2018 with the use of noise abatement systems. Details provided include the OWF name, construction year, water depth, number of foundations piled and pile diameter, and NAS type. Adapted from Philipp (2018).

Construction year	OWF	Depth (m)	Foundation #	Foundation Diameter (m)	NAS BBC	NAS HSD	NAS NMS
2018	Hohe See	40	71	8	x		x
2017	Arkona	23 - 37	60	<= 7.75	x	x	
2017	Merkur	28 - 32	66	7.6 - 7.8	x		x
2017	Nordsee One	26 - 29	54	6.7	x		x
2016/17	Wikinger	36 - 42	70	2.7	x	x *	
2016	Nordergründe	4 - 11.5	18	5.5	x		
2016	Veja Mate	39.3 (average)	67	8.1	x	x	
2016	Gode Wind 01 +02	34 (max)	97	7.5	x		x
2015/16	Sandbank	24.5 - 33.5	72	6.4 - 6.8	x	x	
2014/15	Amrumbank West	19.5 - 24	80	6	x	x	x
2014	Borkum Riffgrund 1	23 - 28	77	5.9	x		x
2014	Butendiek	17 - 22	80	6 - 6.5	x		x
2013/14	Baltic 2	23 - 35	39	5.2 - 6.5	x		
		35 - 44	41	3	x		
2013	Dan Tysk	21 - 32	80	6	x		
2012/14	Nordsee Ost	22 - 25	49	2.4	x		
2012/14	Global Tech 1	38 - 40	80	2.48	x		
2011/12	Meerwind Süd/ Ost	22 - 26	80	5.5	x		

* NAS not used but kept on standby.

Table 2. Number of foundations piled with the use of the NAS BBC, NMS and HSD up to March 2018 in relation to water depth. Adapted from Thomsen and Verfuss (in press).

Water depth range	NAS BBC	NAS NMS	NAS HSD
0 - 20 m	~ 80	~ 70	1
20 - 30 m	> 500	> 230	~ 140
30 - 40 m	> 400	> 100	~ 90
40 - 50 m	~ 50	-	~ 20
Total	> 1,000	> 400	~ 250

In Germany, a BBC has often been used in a configuration in which one or two (in two exceptional cases three) circles of nozzle hoses with increasing radius are laid around the piling position (single or double BBC), and/or in combination with either an NMS or an HSD (Table 1). These configurations/combinations were used to achieve a noise reduction efficacy that kept the piling noise below the prescribed noise thresholds. While the noise thresholds were not always reliably met in the first few years of OWF construction in German waters, from 2014 onwards the use of highly improved NAS enabled a reliable compliance with the German thresholds (Philipp, 2018). A more detailed review of the noise reduction efficacy of the NAS is given in section 8.6.

All three systems (BBC, NMS and HSD) are now commercially available and have been used in several OWF-projects (Table 1, Table 2), and can therefore be considered as at

Technology Readiness Level (TRL) 9 (Full commercial application: Actual system proven in operational environment and manufactured, Table 3). However, as noted above, limited operational experience exists beyond water depths of 40 m (Table 2).

Table 3.Technology Readiness Levels (adapted from Horizon 2020[6]).

Technology Readiness Level	Description
TRL 5: Large scale prototype	Large scale prototype: Technology validated in industrially relevant environment.
TRL 6: Prototype system	Prototype system: Technology demonstrated in industrially relevant environment.
TRL 7: Demonstration system	Demonstration system: System prototype demonstration in operational environment.
TRL 8: First of a kind commercial system	First of a kind commercial system: System complete and qualified.
TRL 9: Full commercial application	Full commercial application: Actual system proven in operational environment and manufactured.

The BBC, NMD and HSD have been frequently applied as noise mitigation tools in OWF-projects (Bellmann *et al*., 2017, Thomsen and Verfuss, in press) and are therefore included in this review. Other NAS discussed in Koschinski and Lüdemann (2013), such as the Little Bubble Curtain, Cofferdams, BEKA-shells and Pile-in-Pipe Piling, were not (or only occasionally) used by the industry, and were therefore excluded from this review.

Two further NAS currently still under development, but which may be promising for future application, were also considered in this review: the “Noise Abatement System” of AdBm Technologies (AdBm-NAS) and the HydroNAS™ of W3G Marine Ltd (HydroNAS). Both systems surround a foundation during piling activity (see section 4). During a first demonstration project in 2014, the AdBm-NAS was tested during the installation of two monopile foundations at the OWF Butendiek in the German North Sea (AdBm Corp, 2014). A first full-scale test was conducted in autumn 2018 in the Belgium North Sea (Thomsen and Verfuss, in press, Wochner, pers. comm.), but further details, other than that the tests were successful, were not available at the time of writing this report (Wochner, pers. comm.). The system will be available for use in OWF-projects in 2019 (Wochner, pers. comm.). The HydroNAS had its first offshore demonstration test at the OWF Kentish Flat, UK (W3G Marine Ltd, 2015a), and is commercially available (Giles, pers. comm.). Further testing has not yet been announced.

In addition to the NAS introduced above, hammers other than impact pile hammers were also considered in this review. These are considered primary noise abatement methods, strictly speaking, and not systems that reduce the noise generated during impact piling. Alternative hammers considered are the Vibratory Hammer (VH) (various suppliers), which vibrates the pile, and thereby causes a temporary reduction in soil resistance, so that the pile can sink into the seabed, and the BLUE Piling Technology from Fistuca BV (BLUE Hammer), which is a new type of pile driver developed to drive a pile using the weight of water (see section 5.4).

VH are commercially available, and have been frequently used for pile installation for the Oil & Gas sector[7] and at several OWF, such as BARD Offshore 1, Riffgat and Global Tech 1 in German waters (Thomsen and Verfuss, in press). They can therefore be considered as TRL 9 (Table 3). In Germany, vibratory pile driving is used in combination with impact pile driving

[6] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
[7] E.g., https://offshore.pve-holland.com/content/661/Oil-amp%3b-Gas/

during OWF foundation installation to demonstrate the axial bearing capacity due to regulatory requirements detailed in BSH (2015) (see section 8.4.2 for further details). The use of VH for pile installation reduces the time needed for impact piling, and thereby the duration of impact piling noise (Koschinski and Lüdemann, 2013). There is, however, a recent example for an OWF monopile solely installed with VH for a research project in the OWF Princess Amalia, in the Netherlands[8]. The BLUE Hammer is currently under development, supported by the Offshore Wind Accelerator (OWA), a collaborative Research, Development and Demonstration (RD&D) programme of the Carbon Trust, UK, and nine offshore wind developers[9]. The BLUE Hammer had a full-scale offshore test (BLUE Pilot) in summer 2018 in the Dutch North Sea (Thomsen and Verfuss, in press). The BLUE Hammer is a novel technology and has only been tested on a single pile so far, and the durability and reliability of the system and whether it can drive continuously on a number of piles is still to be proven (Ørsted pers. comm.). The developer of the BLUE Hammer stated at a workshop in 2018 that the hammer worked but that more development is needed to increase its capacity and reliability. Improvements will be tested on scale in 2019 followed by implementation of a new BLUE Hammer prototype in 2020, with the hammer expected to be commercially available in 2021 (Winkes, pers. comm).

[8] https://www.offshorewind.biz/2018/06/01/dot-monopile-installed-at-princess-amalia-owf/
[9] https://www.carbontrust.com/offshore-wind/owa/

5. NOISE ABATEMENT METHODS CONSIDERED IN THE REVIEW

This review has adopted the division of secondary NAS of Thomsen and Verfuss (in press) into three types: bubble curtains, pile casings and resonators. We also group the hammer technologies being developed to replace conventional hydraulic hammers for mitigation purposes as “alternative hammer”. Table 4 provides an overview of the noise abatement methods that were considered in this review, and the sections below describe them in further detail.

Table 4. Overview of noise abatement methods included in this review, and their suppliers contacted in the survey.

Mitigation measure	Type	Method/System	Abbr	Supplier
Secondary	Bubble curtain	Big bubble curtain	BBC	Hydrotechnick Lübeck GmbH, Weyres Offshore GmbH[10]
	Pile casing	IHC Noise mitigation system	NMS	IHC IQIP
		HydroNAS™	HydroNAS	W3G Marine Ltd
	Resonator	Hydrosound damper	HSD	OffNoise Solutions GmbH
		AdBm Noise Abatement System	AdBm-NAS	AdBm Technologies
Primary	Alternative hammer	BLUE Piling Technology	BLUE Hammer	Fistuca BV
		Vibratory hammer	VH	e.g., CAPE Holland, PVE, PTC Fayat

[10] A third provider of BBC, Continental, seems to have entered the market, which we were made aware of after the end of our questionnaire survey: https://www.continental-corporation.com/en/press/press-releases/sound-insulation-for-marine-life--134416

5.1 Bubble Curtains

Bubble curtains are formed by compressed air that is pumped through one or more nozzle hoses that are laid around the piling position at the seafloor. The air ascends through the nozzles into the water column up to the water surface and thereby builds a curtain of bubbles arising vertically along the tube. Piling sound will be absorbed, reflected and scattered from the ascending air bubbles, and thereby reduced.

There are two types of bubble curtains, the Small Bubble Curtain (SBC) and the BBC. SBCs have been directly attached to the foundation, but this design has not seen its breakthrough in the offshore wind industry (Thomsen and Verfuss, in press). The close proximity to the pile makes the SBC system vulnerable to currents decreasing its effectiveness (see also section 8.4.2 and Figure 10). For deploying a (single) BBC, the hose is laid with a radius of several tens of metres around the piling position, fully enclosing the sound source in order to avoid noise leakage (Figure 1). BBCs come in further configurations such as the double or triple BBC, for which a second or third hose, respectively, is laid around the piling position. A more detailed description of the bubble curtain technology can be found in Nehls *et al*. (2007) and Koschinski and Lüdemann (2013).

Figure 1. Jack-up installation vessel at OWF Borkum West II surrounded by a BBC from HTL. © Hydrotechnik Lübeck GmbH, source: http://www.hydrotechnik-luebeck.de/bildarchiv/

5.2 Casings

Casings are hard or soft shells that enclose the pile with reflective material during the piling activity to keep the sound emitted by the pile trapped within the casing. Casings range from flexible pile sleeves made of different fabrics to hollow steel tubes (Thomsen and Verfuss, in press). Two types of casings were included

5.2.1 NMS, IHC IQIP

The NMS from IHC IQIP (Figure 2) is currently the only NAS in its category commonly used for mitigating noise during OWF construction. The NMS is a casing consisting of a double-walled steel cylinder with sound-insulated connections between the inner and outer wall and an air-filled cavity, with an optional confined bubble curtain (Verfuss, 2014).

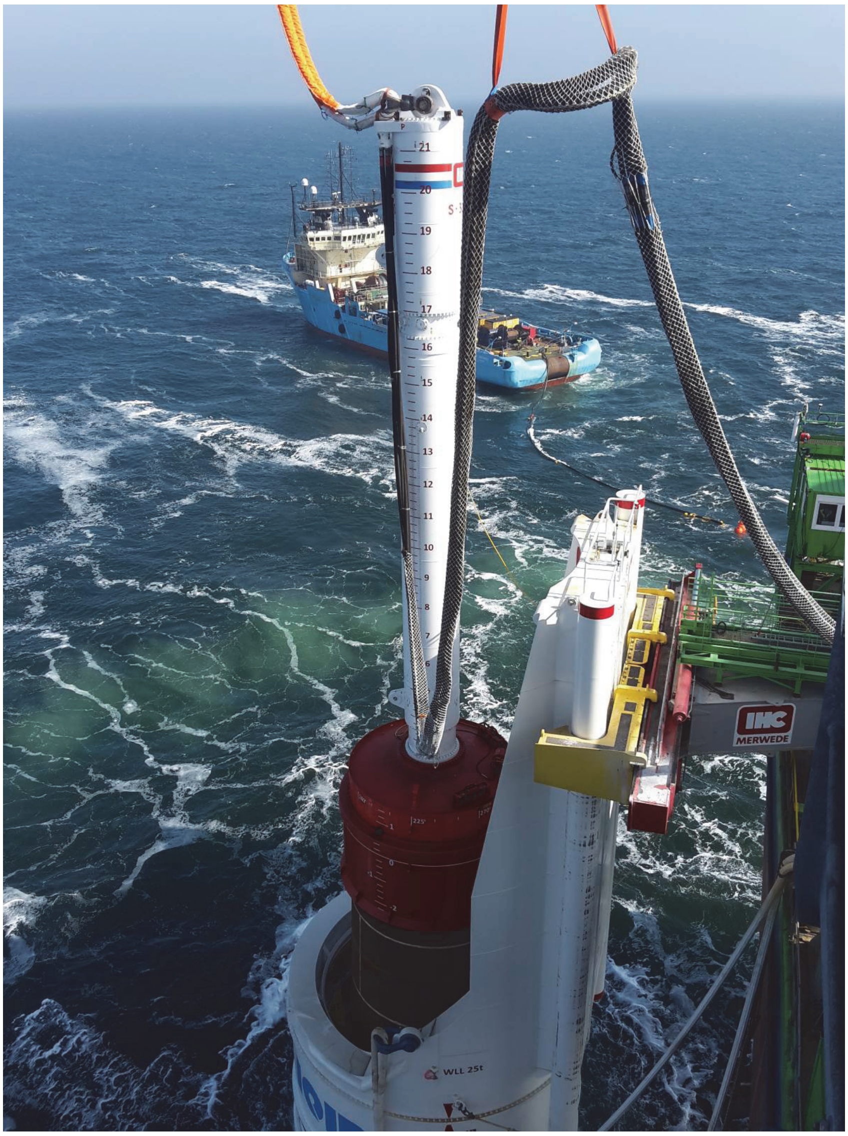

Figure 2. NMS from IHC IQIP deployed from a vessel, surrounding a monopile (dark grey). The hammer (red) is placed on the top of the monopile. © IHC IQIP.

5.2.2 HydroNAS, W3G Marine Limited

The HydroNAS provided by W3G Marine Ltd. (Figure 3) uses a lightweight inflatable fabric, which is restrained internally, to build an unbroken column of air around the pile from the seabed to the surface. Upon the inflation of the fabric, a fixed volume panel of air is created which maintains a specified geometry underwater avoiding ballooning which would otherwise occur. The cells are modular, stackable and can be configured to fit any water depth, pile diameter or any type of pile[11].

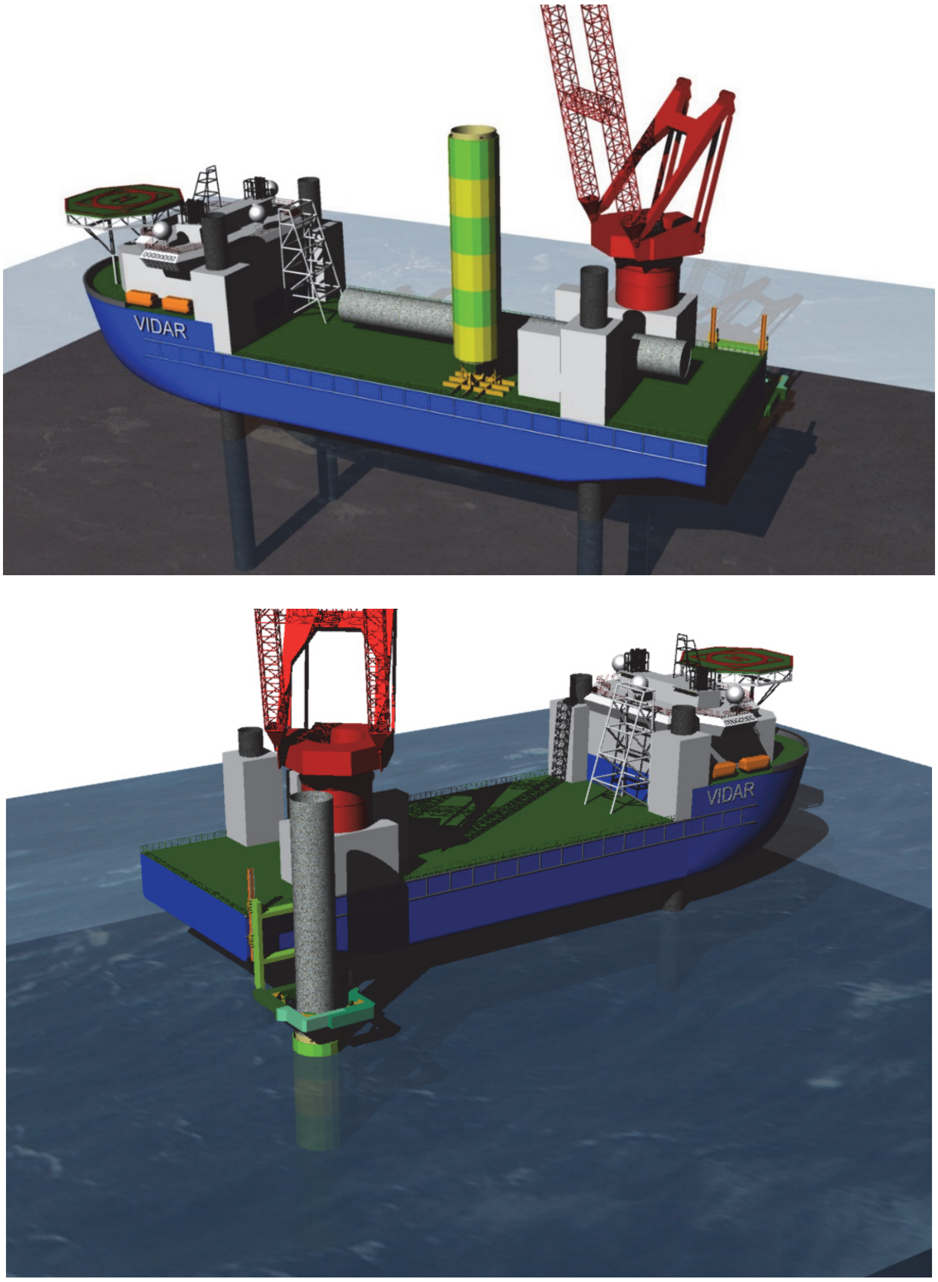

Figure 3. Schematic of the HydroNAS sleeve (green and yellow modules) from W3G stored on deck of an installation vessel next to a pile (grey) (top), and deployment at sea, with the pile being inserted into the HydroNAS (bottom). © W3G Marine Ltd.

[11] http://www.w3gmarine.com/hydronas.html

5.3 Resonator

Resonators consist of an array of (solely or mainly) resonating units that are deployed around the pile to absorb the emitted sound. Unlike with BBCs which are built of ascending air bubbles from a nozzle hose laid at the seafloor, there are a variety of different ways to build resonators. Each supplier has its own resonating material and design. In the following sections, a short description of the two resonators included in this report is given.

5.3.1 HSD, OffNoise Solutions GmbH

The HSD provided by OffNoise Solutions GmbH (Figure 4) consists of a net of foam elements and of air-filled balloons, which are held in a basket fixed at the pile gripper (the unit holding the pile in place during piling). Before the piling activity, the HSD-net is lowered with a ballast weight down to the seafloor and eventually encloses the pile. The HSD-elements are not pure resonators, as they reduce sound also by scattering and reflection. HSD-nets will be tailored to the specific OWF-project, and the “steel ware” (basket, ballast, release system) is not provided by the NAS-supplier but needs to be designed and fabricated by other contractors.

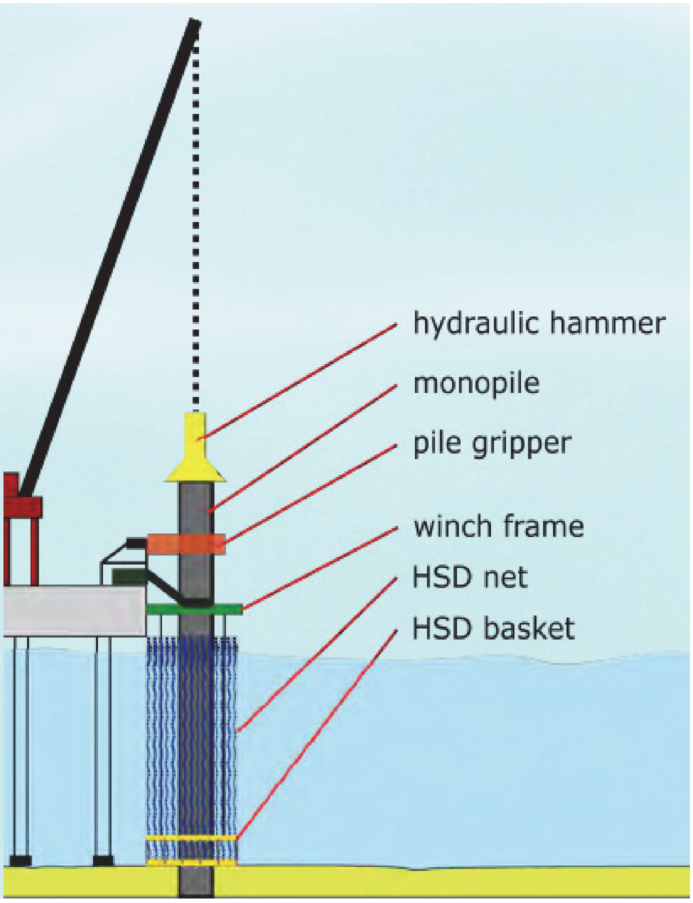

Figure 4. HSD-net by OffNoise Solutions GmbH lifted by a crane on land (left). The height of the net is 40 m. Schematic of the HSD-deployment during monopole installation from a jacked-up platform (right). © OffNoise Solution GmbH.

5.3.2 AdBm-NAS, AdBm Technologies

The AdBm-NAS provided by AdBm Technologies LLC (AdBm) (Figure 5) consists of standard size panels with submersible air-filled Helmholtz resonators that encircle the pile during construction[12]. The AdBm-NAS has to be tailored to the specific OWF-project. To accommodate the particular needs of a specific project, the NAS-supplier offers the resonator panels either with a frame or on their own. In the latter case, the steel framework holding the system would then need to be designed and fabricated by another contractor.

Figure 5. AdBm-NAS system from AdBm Technologies showing the resonators in air to test that the system opens properly (left), and the system deployed around a pile at the OWF Norther, Belgium during the full-scale test (right). © AdBm Technologies.

5.4 Alternative hammers

Two types of alternative hammers have been considered in this survey that can potentially be used to install a pile with less noise emission than a conventional hydraulic impact hammer. These are the VH and BLUE Hammer.

The VH (Figure 6) can be used to vibrate the pile with a certain low vibrating frequency vertically into the seabed. Pairs of counter-rotating eccentric masses generate an upwards and downwards movement, resulting in a vertical amplitude which results in a temporary reduction in soil resistance, which allows the pile to sink into the soil (van Wijngaarden, pers. comm.).

[12] http://adbmtech.com/technology/

Figure 6. A VH from PVE on a 2.5 m diameter pile used to install a tripod at the OWF Global Tech 1, Germany © PVE (left) and a VH from CAPE Holland vibrating a 4 m diameter monopile at OWF Princess Amalia, the Netherlands © CAPE Holland (right).

The BLUE Hammer from Fistuca BV (Figure 7) consists of a steel housing that can be filled with a large water column. The water column is accelerated upwards before dropping onto the pile. High energy levels are achievable which allow a long-lasting blow with high force levels. The cycle of raising and dropping the water column is repeated (Thomsen and Verfuss, in press).

Figure 7.Fistuca's BLUE Hammer deployed on an installation vessel placed on top of a monopile. © Michael Stephenson, The Carbon Trust.

6. FACTORS CONSIDERED IN THE NAS-REVIEW

For the review of the NAS, technical, environmental and species-specific factors were considered in relation to:

- The scope of application, i.e., in which situations the NAS can be applied,
- The logistical requirements and limitations for the deployment and operation of the NAS to inform the associated cost implications,
- The environmental factors potentially influencing and limiting the deployment and operation of NAS, to link the suitability of the systems to the environmental conditions prevailing in the potential Scottish OWF sites,
- The direct cost implications associated with the use of NAS, and
- The noise reduction efficacy, i.e., how environmental and technical factors influence the efficacy, and for which target species the NAS might be most suitable.

These factors are explained in the following sections in further detail.

6.1 Technical factors

It is important to know which foundation types the NAS has been used for, and what the restricting dimensions of the substructures are. The most common wind turbine foundations currently installed with impact piling are monopiles and piled jackets. During monopile installation, one large pile is driven into the seabed. Pile diameter has increased over the last decade, e.g., in Germany from less than 3 m in 2012 to up to 8 m in 2018 (Bellmann *et al*., 2018). Larger pile diameters are planned for the future to accommodate larger wind turbines with rated capacities of more than 10 MW (T. Verfuss, pers. comm.). Piled jackets are substructures that are installed with three to six pin piles. These piles have a considerably smaller diameter than monopiles, but the jacket itself will occupy a larger footprint on the seafloor. For jacket installation, two installation options exist: pre-piling or post-piling. In pre-piling, the pin piles are positioned with the help of a template, then driven into the seabed, and finally the jacket is mounted onto the pin piles. In post-piling, the jacket is placed on the seabed, and then fixed with pin piles.

The logistical requirements of the use of a NAS may result in potential restrictions and **indirect cost** implications. Time delay in the construction schedule can cause indirect costs, as rental and stand-by costs of the installation vessel and the risk of vessel unavailability increase. Decreased deck space on the installation vessel due to the need to store the NAS may result in less space for substructures and other material that is needed for installation and could lead to the need to travel more often from the harbour to the construction site.

System weight, the potential need for logistical support, the risk of the system malfunctioning (and consequently its potential non-availability) and the requirements of a risk mitigation plan as well as any potential special HSE requirements, are factors that need to be considered to fully evaluate the applicability of a system. **Direct costs** are important to consider when planning to deploy a NAS alongside piling activities, these do not only include the rental costs of the NAS, but may also include costs for auxiliary equipment, staff and auxiliary vessels.

6.2 Environmental factors

The following environmental factors and their influence on the deployment and operation of the NAS were considered:

- Water depth: some NAS may only be suitable up to certain water depths, or the suitability of a system for specific water depths may not yet have been field tested.

Variation in water depth across a given OWF construction site may also restrict the application of a NAS,

- Soil geology: this may affect the deployment and / or operation of the NAS,
- Speed of local currents: currents may challenge the deployment of a NAS or reduce its efficacy, and
- Significant wave height and wind speed: deployment and / or operation of a NAS may be restricted by these parameters, e.g., lifting operations can only be performed up to certain wind speeds, and deployment or recovery are restricted to certain wave heights.

6.3 Species specific factors

High peak sound pressure levels (L_{pk}) can induce auditory injury, such as permanent (PTS) or temporary (TTS) threshold shift, in marine mammals and fish regardless of the frequency content of the noise (National Marine Fisheries Service, 2018, Popper *et al*., 2014). High sound exposure levels (SEL) (i.e., the sound energy an animal is exposed to) can also induce auditory injury in marine mammals and fish. National Marine Fisheries Service (2018) proposed a set of frequency weighting functions for species groups that considered their hearing abilities. It is recommended that these frequency weighting functions are applied before the SEL is determined to evaluate the potential harm of anthropogenic sound. The criteria provided in National Marine Fisheries Service (2018) is currently the most up to date guidance for noise impact assessment of auditory injury for marine mammals, and is commonly used in the UK in environmental impact assessments for OWF since it was first published in 2016 (National Marine Fisheries Service, 2016). In addition to providing thresholds for unweighted zero-to-peak sound pressure level ($L_{pk,\ flat}$), they also set a threshold for the sound energy that an animal accumulates during an anthropogenic activity within a 24 hour window, as the risk of auditory injury increases with increasing amount of total energy received by an animal (the cumulative sound exposure level, SEL_{cum}).

One approach to calculate auditory injury impact ranges based on SEL_{cum} proposed by National Marine Fisheries Service (2018) is the “safe distance” method, a model approach that determines at what distance from a source a receiver would have to remain in order to not exceed a predetermined exposure threshold. In the description of this approach, they assume a stationary animal and a moving sound source (e.g., vessel). In UK-noise impact assessments for OWF, this approach is often modified with the sound source being stationary and the animals predicted to move away from the sound source. The auditory impact ranges based on SEL_{cum} are then determined by the SEL of each single strike (SEL_{ss}), the blow rate of a pile installation, the number of blows, the sound propagation conditions around the pile location and the assumptions made regarding the responsive movement of the animal (e.g. swim speed of the animal moving away from the sound source), as this determines the amount of sound energy an animal receives with each pile strike. The use of NAS can influence the magnitude of the SEL_{ss}, which is the only component influencing the SEL_{cum} that will be evaluated in this report. Further detail on the derivation of SEL_{ss} and SEL_{cum} can be found in National Marine Fisheries Service (2018).

National Marine Fisheries Service (2018) weighting functions relevant for this review are provided for the following groups and depicted in Figure 8, and their generalised hearing ranges, along with those of fish species groups, are provided in Table 5:

- Low-frequency (LF) cetaceans (baleen whales),
- Mid-frequency (MF) cetaceans (e.g., dolphins, beaked whales, bottlenose whales),
- High-frequency (HF) cetaceans (e.g., true porpoises, *Kogia*, *Lagenorhynchus* sp.), and
- Phocid pinnipeds (PW) underwater.

Table 5. Hearing range of low-, mid- and high-frequency cetaceans (LF, MF and HF cet) and phocid pinnipeds under water (PW), and of fish species lacking swim bladders (– swim bladder), with swim bladders that do not play a role in hearing or that have a swim bladder not closely connected to the ear (+ swim bladder) and with special auditory structures mechanically linking the swim bladder to the ear (++ swim bladder).

Animal group		Hearing range
Marine mammals	PW	50 Hz to 86 kHz
	LF cet	7 Hz to 35 kHz
	MF cet	150 Hz to 160 kHz
	HF cet	275 Hz to 160 kHz
Fish	- swim bladder	below 100 Hz
	+ swim bladder	up to 500 Hz
	++ swim bladder	in kHz region

Whilst National Marine Fisheries Service (2018) thresholds are currently used, Southall (2018) announced a forthcoming publication (Southall *et al.*, 2019), which will include a revision of the noise exposure criteria. These are fundamentally based on the same quantitative process as the National Marine Fisheries Service (2018) criteria, but with further divisions and alternative naming of the hearing groups and cover all marine mammals (whilst National Marine Fisheries Service (2018) is focused on US species). As these revisions are based on the same quantitative processes, the information presented in this report will also be valid in the light of the updated noise exposure criteria.

Due to species specific hearing sensitivities, it is important to evaluate the frequency specific noise reduction properties of NAS. The species groups LF cetaceans and PW have good low frequency hearing but their hearing also ranges into the ultrasound region (above 20 kHz).

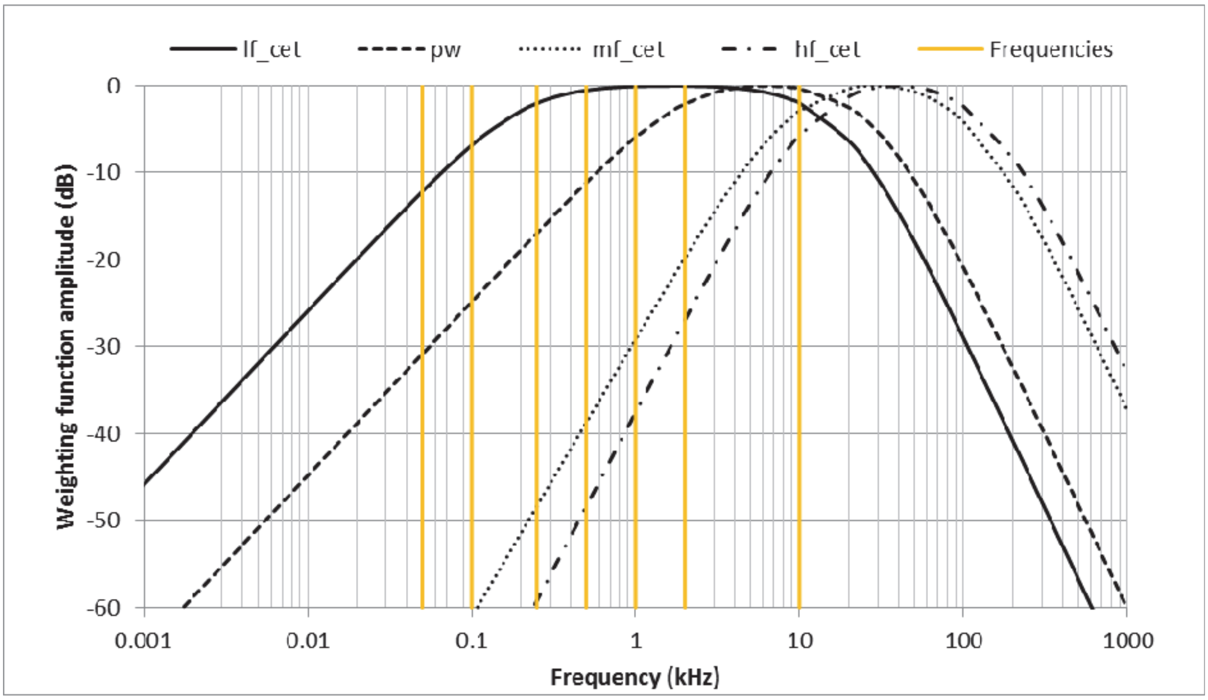

Figure 8. National Marine Fisheries Service (2018) weighting functions for high frequency cetacean (hf_cet), pinnipeds in water (pw), mid frequency cetacean (mf_cet) and low frequency cetacean (lf_cet). The yellow vertical lines indicate the frequencies that were used to evaluate the efficacy of the NAS.

The evaluation of the broadband SEL will therefore give an estimate of the impact reduction efficacy for species belonging to these groups. For species with less sensitivity to low frequencies (species groups MF and HF cetaceans), the evaluation of the level of noise reduction above 250 Hz and 1 kHz respectively is required to estimate the impact reduction efficacy. While 250 Hz is at the lower end of the hearing range of MF and slightly below the hearing range of HF species, these species become more sensitive at frequencies above 1 kHz.

Popper *et al*. (2014) proposed the evaluation of the risk of auditory injury in fish based on broadband levels due to the high variety in the hearing abilities of the different fish species and therefore the inability to create a species group dependent frequency weighting. However, they state that fish lacking swim bladders or with swim bladders that do not play a role in hearing are only sensitive to a narrow band of frequencies, where the sensitivity to sound can be below 100 Hz. Fish with swim bladders that are close, but not directly connected to the ear, can hear up to about 500 Hz. Fish with special auditory structures mechanically linking the swim bladder to the ear are sensitive to frequencies up to several kHz. The evaluation of the reduction in broadband SEL as well as the reduction in SEL for the frequency band below 100 Hz and at and below 500 Hz, respectively, will allow the estimation of the impact reduction for each fish species groups.

To understand the efficacy of the NAS, the reduction, compared to unmitigated piling, for the unweighted sound pressure level and the sound exposure level of a single pile strike was examined. To evaluate the species-specific efficacy, the frequency spectra of mitigated and unmitigated piling sound were compared. The reduction in SEL at a range of frequencies was evaluated. The frequencies 50 Hz, 100 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz and 10 kHz were selected to demonstrate how the reduction in noise levels varies with increasing frequency. The frequencies were selected to have at least one reference at the lower end of each marine animal species group's hearing range (Table 5), and at least one reference at or near the upper flat part of the marine mammal species group's weighting curve (Figure 8), i.e., the frequency range that will mainly be considered in the evaluation of auditory injury. While particle motion is an important sound parameter for fish, no data on particle motion are available in relation to OWF construction and NAS, and could therefore not be considered in this review.

7. ENVIRONMENTAL CONDITIONS AT SCOTTISH OFFSHORE WIND FARM SITES

The OWF sites in Scottish waters that are considered in this review have been obtained from Crown Estate Scotland (CES), Scottish Government (2018) and associated documents[13]. Only those sites at which piled foundations are planned or likely were considered in the review, plus the existing OWF Robin Rigg, as it represents a very different hydrodynamic regime (Table 6, Figure 9).

Table 6. Consented and potential offshore windfarm sites in Scottish waters included in this review. Figure 9 shows the location of these sites. Information: TCE, https://www.4coffshore.com/. N/A = not applicable, tbd = to be determined.

Type	#	OWF name	Tenant	Area (km^2)	Foundation
Built	1	Robin Rigg	EON C&R UK Robin Rigg East Ltd	18	Monopile
Consented	2	Moray West	Moray Offshore Windfarm (West) Ltd	225	Various incl piled
	3	Moray East	Moray Offshore Windfarm (East) Ltd	295	Jacket
	4	SeaGreen Alpha	Seagreen Alpha Wind Energy Ltd	197	Various incl piled
	5	SeaGreen Bravo	Seagreen Bravo Wind Energy Ltd	194	Various incl piled
	6	Inch Cape	Inch Cape Offshore Ltd	149	Various incl piled
	7	Neart Na Gaoithe	Neart Na Gaoithe Offshore Wind	105	Jacket
Potential OWF areas[14]	8	NE7	N/A	86	tbd
	9	E1	N/A	588	tbd
	10	W3	N/A	554	tbd

[13] https://consult.gov.scot/marine-scotland/offshore-wind-scoping/

[14] SNH Note: The potential future lease areas have changed since this report was written. Marine Scotland is due to consult on a suite of possible option areas in late summer 2019. While the three potential offshore wind sites depicted here may not now be coincident with the option areas ultimately consulted upon, they are (at time of press) indicative of locations currently under consideration.

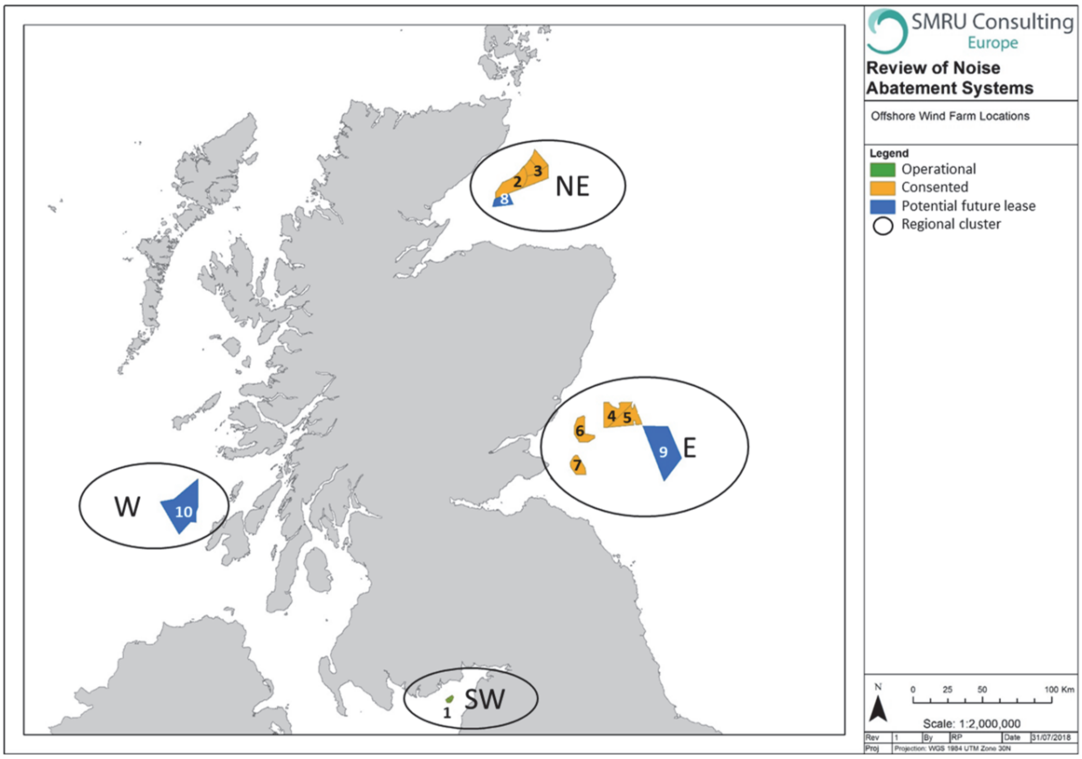

Figure 9. Location of the offshore windfarm sites in Scottish waters that are considered in this review (numbering refers to that provided in Table 6).

Environmental data were obtained from ABPmer (2008a), a main reference for regional scale descriptions of offshore renewable energy resource and a tool to screen for potential development sites (ABPmer, 2008b). ABPmer sourced 7-year data sets (2000 – 2007) of wind and wave data from a model suite operated by the Met Office. The wave data are based on a grid with a spatial resolution of 12 km; wind speed is based on hourly data for each of the wave grid cells. Tidal current data are based on an ocean turbulence model (ABPmer, 2008b) for grid cells with a horizontal resolution of 1 nautical mile. The mean spring peak current and mean neap peak current used in this report provide the average value for the peak flow of the current. They also offer bathymetric data revealing the mean water depth for each grid cell. For more information on these data see ABPmer (2008b).

To characterise the environmental conditions at the OWF sites, the minimum, mean and maximum water depth, peak current speed, minimum, mean and maximum wind speed, and significant wave height within the boundaries of the OWF-project were extracted from the ABPmer (2008a) data sets. The OWF-sites were grouped into regional clusters:

- NE: North-Eastern Scottish waters: OWF # 2, 3 and 8,
- E: Eastern Scottish waters: OWF # 4-7 and 9,
- SW: South-West Scottish waters: OWF # 1, and
- W: Western Scottish waters: OWF # 10.

Table 7 provides the results for water depths and peak currents speed, Table 8 summarises the wind speed per season, and Table 9 provides an overview of the mean significant wave heights by season.

Table 7. Water depth and peak current speed at mean neap tide and mean spring tide for the windfarm sites listed in Table 3. Marked in light grey are peak current speeds > 1 m/s to enable an easier comparison with the operational limitations of NAS and installation vessels (section 8.4.2). Note that water depth and peak current are averaged over 1 nautical mile grid cells. Source: ABPmer (2008a).

Region	OWF #	Water depth (m)				Peak current speed (m/s)					
						Mean neap tide			Mean spring tide		
		Min	Mean	Max	Range	Min	Mean	Max	Min	Mean	Max
NE	2	39	45	53	14	0.1	0.2	0.2	0.2	0.3	0.5
	3	40	48	57	17	0.1	0.2	0.3	0.2	0.4	0.5
	8	49	53	58	9	0.1	0.1	0.1	0.2	0.2	0.2
E	4	47	52	57	10	0.3	0.3	0.4	0.5	0.6	0.7
	5	50	54	58	8	0.3	0.3	0.3	0.5	0.6	0.6
	6	42	49	54	12	0.3	0.3	0.3	0.5	0.6	0.6
	7	46	51	54	8	0.2	0.2	0.3	0.4	0.4	0.5
	9	50	56	63	13	0.2	0.2	0.3	0.5	0.5	0.6
SW	1	7	10	13	6	0.7	0.7	0.8	1.2	1.3	1.4
W	10	19	47	77	58	0.2	0.4	1.0	0.4	0.8	1.8

Table 8. Mean wind speed at 80 m height above sea level for the windfarm sites listed in Table 3. Provided are the minimum, mean and maximum wind speed per season, rounded to the first decimal point. Marked are values between 10 and <11 in light grey, 11 and <12 in grey, and ≥12 in black to enable an easier comparison with the operational limitations of NAS and installation vessels (section 8.4.2). Source: ABPmer (2008a).

Region	OWF #	Wind speed @ 80 m (m/s)											
		Spring			Summer			Autumn			Winter		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NE	2	8.0	8.6	8.9	6.1	6.8	7.2	9.0	9.7	10.0	9.9	10.7	11.1
	3	8.7	8.9	9.2	6.9	7.1	7.4	9.7	9.9	10.3	10.7	11.0	11.4
	8	8.0	8.3	8.5	6.1	6.5	6.8	9.0	9.3	9.6	9.9	10.3	10.7
E	4	8.7	9.1	9.3	7.3	7.6	7.8	10.0	10.3	10.6	11.4	11.8	12.1
	5	9.0	9.2	9.4	7.5	7.8	7.9	10.2	10.5	10.7	11.7	12.0	12.2
	6	7.8	8.4	8.8	6.4	7.0	7.3	8.9	9.6	10.0	10.1	10.9	11.4
	7	8.2	8.4	8.7	6.7	7.0	7.3	9.3	9.6	9.9	10.6	11.0	11.4
	9	9.3	9.4	9.4	7.7	7.9	8.0	10.4	10.6	10.7	12.1	12.2	12.3
SW	1	6.0	7.3	7.6	4.9	6.0	6.3	6.3	8.2	8.6	7.1	9.1	9.7
W	10	8.7	9.4	9.8	6.9	7.5	7.8	9.9	10.9	11.2	11.0	12.2	12.6

Table 9. Mean significant wave height for the wind farm sites listed in Table 3. Provided are the minimum, mean and maximum wind speed per season, rounded to the first decimal point. Marked are values between 1.5 and <2 in light grey, 2 and <2.5 in grey, and ≥2.5 in black to enable an easier comparison with the operational limitations of NAS and installation vessels (section 8.4.2). Source: ABPmer (2008a).

Region	OWF #	Mean significant wave height (m)											
		Spring			Summer			Autumn			Winter		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NE	2	1.2	1.4	1.5	0.8	0.9	1.0	1.4	1.6	1.7	1.5	1.8	1.9
	3	1.4	1.5	1.6	0.9	1.0	1.1	1.6	1.7	1.8	1.8	1.9	2.0
	8	1.2	1.2	1.3	0.8	0.8	0.9	1.3	1.4	1.5	1.5	1.6	1.7
E	4	1.4	1.5	1.6	1.0	1.1	1.2	1.6	1.7	1.8	1.8	2.0	2.1
	5	1.4	1.5	1.6	1.0	1.1	1.2	1.6	1.7	1.8	1.9	2.0	2.2
	6	1.2	1.3	1.3	0.9	0.9	1.0	1.4	1.5	1.5	1.6	1.6	1.7
	7	1.1	1.2	1.3	0.8	0.9	0.9	1.3	1.4	1.5	1.4	1.6	1.7
	9	1.6	1.6	1.7	1.1	1.2	1.2	1.8	1.8	1.9	2.1	2.2	2.3
SW	1	0.6	0.8	0.8	0.5	0.6	0.6	0.6	0.9	1.0	0.7	1.0	1.1
W	10	1.7	1.9	2.1	1.3	1.4	1.5	2.0	2.2	2.4	2.5	2.7	3.0

8. SURVEY RESULTS

The following section presents information on the NAS listed in section 5 received from the NAS-suppliers and NAS-users by means of the completed questionnaires and subsequent clarifications. This information is mainly summarised and presented in tables. The review of the NAS is supplemented by information retrieved through interviews and the literature. While the vibratory hammer and the BLUE Hammer are strictly speaking not NAS, these have been considered here as NAS in a wider sense. When referring to NAS in the following text, this will therefore include alternative hammers.

It has to be emphasised that the review is based on a questionnaire and interview-based survey with input from NAS-suppliers, NAS-users and literature. Questions might have been interpreted differently or answered with a project specific context, and answers may be informed by experience from earlier projects as well as from later projects (i.e., at different development stages of the NAS). Questionnaires completed by NAS-users did lack input for specific sections, where the NAS-users lacked experience on the topic of that section. Another limitation of this survey was that companies with field experience were often restricted by non-disclosure-agreements and therefore had to decline the completion of the questionnaire. The results of the survey can therefore only give an indication on the technical limitations, and do not represent an in-depth assessment of the NAS.

For a full assessment, an evaluation must be based on the requirements of the specific project and the OWF-project site guided by engineers and field-experienced experts.

8.1 Questionnaire responses

All providers of noise abatement methods (NAS-suppliers) listed in Table 4 were invited to participate in the survey and to complete the questionnaire (Annex 1) as well as NAS-experienced OWF-developers, installation contractors and noise monitoring service providers. Twenty questionnaires were completed (Table 10).

8.2 Scope of NAS application

All NAS-suppliers stated that their system can be used for piling activities with the hammer operated either above the water or below the water surface. For the BLUE-Hammer one NAS-user indicated that this system has not yet been used for underwater piling.

8.2.1 Bubble curtains

The BBCs are around the pile, usually at distances up to 250 m, although HTL stated a maximum distance of 400 m for their system (Table 11). With this radius, monopiles as well as pre-piled or post-piled jackets can be surrounded by the BBC, without any restrictions with regard to pile diameter and pile length for monopiles and jacket footprint and pin pile diameter for jacket foundations (Table 11).

8.2.2 Casings

The casings are applied close to the pile (Table 11). According to the NAS-supplier, the NMS 8000 can be used with monopiles up to 8.8 m diameter and in water depths up to 45 m and is offered as part of an integrated monopile installer. Two NAS-users stated a pile diameter limit of 8 m and 8.5 m, respectively. An NMS-model for pre-piled jackets is currently only available as a design but not available for offshore applications (NAS-users). No information was provided on whether the NMS can be used for post-piled jackets. According to the NAS-supplier, the HydroNAS can be used for monopiles without any restrictions on the pile diameter and length, and also for both pre-and post-piled jackets, with the restriction that it needs to be built into the piling template, and is, so far, untested.

Table 10. Overview of the systems for which information was given in a questionnaire, and the time frame and technology readiness level (TRL) (as judged by the specific supplier or user) the information refers to. The target group specifies if a questionnaire was completed by a NAS-supplier or NAS-user (shaded light blue).

Type	Target group	Company: model (further information)	Time frame information refers to < 2012	2012-2014	2015-2017	> 2017	TRL
Bubble curtains	Supplier	HTL: BBC HY100/75	x	x	x	x	9
	Supplier	Weyres	x	x	x	x	9
	User	HTL: BBC HY75	x	x	x	x	9
	User	HTL: BBC HY75 (used with NMS)		x			9
	User	HTL: BBC, Weyres: BBC			x		9
	User	HTL: BBC (used with HSD)			x		9
	User	HTL: BBC	x				9
Casings	Supplier	IHC IQIP: NMS8000			x	x	9
	User	IHC IQIP: NMS8000				x	9
	User	IHC IQIP: NMS7000/22 (used with HTL)		x			9
	User	IHC IQIP: NMS8000			x		9
	Supplier	W3G: HydroNAS Prototype		x			5-6
Resonators	Supplier	OffNoise-Solution: HSD-net	x	x	x	x	9
	User	OffNoise-Solution: HSD individual systems	x	x	x	x	9
	User	OffNoise-Solution: HSD-j (for jacket)			x		7
	User	OffNoise-Solution: HSD-system (used with HTL)			x		9
	Supplier	AdBm Technologies: AdBm-NAS				x	7
Alternative hammers	Supplier	Fistuca: BLUE 25M				x	6
	Supplier	PVL: Various VH models		x	x	x	9
	Supplier	CAPE-Holland: Various VH models			x	x	9

Table 11. Scope of application for the NAS. The table is based on information provided by the NAS-suppliers and NAS-users (shaded blue). - = no information given by supplier/user. Please see text for further details on the restrictions.

NAS-system	Distance to pile (m)	Supported foundation type		
		Monopile	Jacket	
			Pre-piled	Post-piled
BBC-HTL	20 to 400	Yes	Yes	Yes
BBC-Weyres	40 to 150	Yes	Yes	Yes
BBC-users	38 to 250	Yes	Yes	Yes
NMS	< 3	With restrictions	-	-
NMS-user	< 3	With restrictions	With restrictions	-
HydroNAS	< 3	Yes	Yes	With restrictions
HSD	< 3	Yes	Yes	Yes
HSD-user	< 3	Yes	With restrictions	-
AdBm-NAS	< 3	Yes	Yes	Yes
BLUE Hammer	0	Yes	With restrictions	With restrictions
VH-CAPE Holland	0	Yes	Yes	Yes
VH-PVE	0	Yes	Yes	Yes

8.2.3 Resonators

The resonators are applied close to the pile (Table 11). They can, according to the NAS-suppliers, be used for monopiles and pre-, as well as post-piled jackets. According to one NAS-user, the HSD can be applied for monopiles with a diameter up to 11 m, although other NAS-users confirmed that the system should be able to accommodate larger diameters, as the system is easily scalable. While one NAS-user stated that HSD for pre-piled jackets is currently only available as a design, another NAS-user shared their offshore-experience with a HSD-system prototype applied for the installation of pre-piled jackets (HSD-j). It was stated that the HSD-j is limited to the pile diameter, and that it does not cover the footprint of the piling-template. One NAS-user confirmed that there is only limited experience with the use of HSD for jacket foundations.

8.2.4 Alternative hammers

The VH and BLUE Hammer are applied directly to the pile as they replace the conventional impact pile-driver. The BLUE Hammer, which is still under development, is designed to fully replace the hydraulic hammer. Vibratory piling is rarely used in Europe to drive piles to their final depths (GDG, 2015). The reason behind this is that vibrated piles are thought to have a reduced axial (i.e., on the pile's axis) bearing capacity. To ensure the required axial bearing capacity, the German Society for Geotechnics (Deutsche Gesellschaft für Geotechnik, 2007) recommends the use of an impact pile-driver for the last metres of pile installation, which is a requirement in German OWF-projects (BSH, 2015) (such as OWF Global Tech 1 for pin-piles and OWF Riffgat for monopiles, Thomsen and Verfuss (in press)). Regulations specific to this matter are discussed in GDG (2015). Recent examples of a monopile solely installed with a VH (at the OWF Princess Amalia, the Netherlands[15]), and RD&D projects conducted by OWF developers (e.g., LeBlanc Thilsted *et al*., 2013) or funded by joined industry programmes (such as the Vibro Driving project[16] from the OWA and the Gentle Driving of

[15] https://www.offshorewind.biz/2018/06/01/dot-monopile-installed-at-princess-amalia-owf/
[16] https://www.carbontrust.com/offshore-wind/owa/demonstration/

Piles project[17] from ‘Growth through Research, development & demonstration in Offshore Wind’ (GROW[18])) show that efforts are being undertaken to prove the VH as a viable alternative to impact hammer. LeBlanc Thilsted *et al*. (2013) stated, based on vibro-drive trials conducted at the Anhold OWF in Danish waters, that the axial bearing capacity of a vibro-driven monopile in dense sand (as prevailing in the North Sea) is not critical and validation using an impact hammer should not be a requirement. The VH supplier CAPE Holland also noted that, whilst it seems reasonable to demonstrate the axial bearing capacity for pin piles (following the BSH requirement; see above), this requirement seems, in CAPE Holland’s opinion, superfluous for monopiles, as the theoretical axial bearing capacity of monopiles is many times higher than needed to carry the weight of a turbine. CAPE Holland note in this context that the lateral (i.e., sideward to the pile’s axis) bearing capacity would be more important to be considered for monopiles, however, the lateral bearing capacity cannot be determined with an impact hammer. An OWA project led by Innogy SE revealed that the lateral bearing capacity of impact and vibratory driven piles in sands is comparable and the variation calculable, and that the installation induced fatigue on vibrated piles is significantly below that of impact driven piles (Meyer, 2018). A full-scale OWF installation solely by vibropiling has yet not been demonstrated (Meyer, 2018). The need to combine vibropiling with impact piling in Germany results in the use of two hammers, a VH and a conventional hydraulic hammer, to bring the pile to target depth and apply a dynamic proof load.

In addition to the uncertainties regarding bearing capacity, one NAS-user highlighted that the drivability conditions for VHs are hard to predict which presents a risk to the project, as there may be uncertainty as to whether piles can be fully installed using this method (Thomsen and Verfuss, in press). One NAS-user stated that projects using only vibropiling may not be certifiable in some markets due to the uncertainties in the soil reaction and stability of the pile. However, one VH supplier pointed out that the predictions of drivability have improved over the last few years and that the predictions of the supplier’s geotechnical consultant on the point of refusals are very accurate. They also pointed out that it is important for each project to determine the correct configuration for a VH and to assess the risk of refusal, as would be needed for an impact hammer.

According to the NAS-suppliers, there are no restrictions for VHs and BLUE Hammer with regard to the monopile pile diameter and length (Table 11). The VHs can also be used for installing pre-piled and post-piled jackets. The BLUE Hammer can, according to the NAS-supplier, also be used for installing jacket foundations, but the overturning stability (risk of tilting) would need to be assessed for pre-piled jackets, and only piles that will be driven down vertically can be installed for post-piled jackets. Demonstration (and the current version) of the BLUE hammer is however only designed for monopile installation, and it has not yet been demonstrated that it can be used for jacket foundations (NAS-user).

8.3 Logistical requirements for NAS

8.3.1 Mobilisation time

In the questionnaire, the mobilisation time for a NAS-system is defined as “from placing an order to arrival of the system at the quayside” (Annex 1, question 10). Due to different interpretations of the definition of mobilisation, the resulting information received was quite variable amongst the systems (Table 12). In subsequent communications with NAS suppliers, it was clarified that some suppliers answered this question in relation to the time that it would take for them to deliver a system to an end user where the system was already in stock and the order process had been completed. Whereas others responded with the time required for the system to be fully assembled or newly built. Where possible, both possibilities are given. This explains the range between the shortest and longest time

[17] https://www.grow-offshorewind.nl/project/gentle-driving-of-piles
[18] https://www.grow-offshorewind.nl/about

periods stated in Table 12. NAS-users also highlighted that the mobilisation time often depends on the availability of a system and whether modifications need to be done to the system for using it in a specific OWF-project. The specification of the installation spread (the aggregate of equipment used for installation) of an OWF-project is decided a minimum of one year ahead of construction (Philipp, 2018), therefore a mobilisation time of several months for a NAS should generally not be an issue for an OWF-project if the use of a NAS is certain in the early phase of a project.

8.3.1.1 Bubble curtains

HTL specified that a mobilisation time of one week would be needed for the supply of a double BBC-system that was held in stock for a monopile installation, while several months would be needed to prepare a system with a new nozzle hose from the point of order (Table 12). The mobilisation of a BBC within a couple of days specified by Weyres (Table 12) refers to existing contracts and the time needed to set up the system on the vessel. According to the NAS-users, the mobilisation of a BBC (Table 12) depends on the availability of the systems, as only two suppliers are currently providing these systems. Another NAS-user had the general experience that the mobilisation time can be short when urgently needed or if the system were only needed for a short time, but long when a full new system needed to be mobilised.

8.3.1.2 Casings

IHC IQIP also specified that the mobilisation time (Table 12) very much depends on the availability of a system that suits a specific OWF-project. To their home port in Vlissingen (NL) a system can be supplied within one day. Transportation of the system to another harbour other than the home port may increase the delivery time depending on vessel availability and weather conditions. If the system needs to be newly built for a specific OWF project, this can take up to one year. One NAS-user specified that the mobilisation time could take two years, if a project specific system for a larger pile size is needed.

8.3.1.3 Resonators

The resonator systems have a more unified reported mobilisation time of two to three months (Table 12). HSD supplier OffNoise Solutions states that their mobilisation time includes manufacturing the individual nets and the steel works (i.e., the ballast box, which carries the ballast to sink the HSD-net to the seafloor, and the basket that holds the HSD-net during transport and deployment). Mobilisation time experienced by the NAS-users range from one month to 3 - 6 months, which would then include engineering, fabrication and delivery.

8.3.1.4 Alternative Hammers

The mobilisation of the BLUE Hammer depends on its availability, and it would take up to 12 months to build a new system. CAPE Holland provided different mobilisation times (from order to delivery) depending on whether it refers to existing VHs able to install up to 6 m diameter piles (1 - 12 months), or to new build VHs for larger piles (18 months), while it takes 1 to 5 days to mobilise a VH from the port onto the deck of a vessel. PVE reported that they can mobilise their VH system from arrival at the port onto the vessel within a minimum of 3 days (Table 12).

8.3.2 Time for deployment and recovery

The time needed to deploy and recover a NAS may influence the piling process of a foundation and may prolong, or lead to delays in, the construction schedule. For all the systems, except the alternative hammers, these times are weather sensitive, and delays may occur due to weather limitations (see section 8.4.2). All other factors are discussed specific to each NAS below.

Table 12. Time required for mobilisation, deployment and recovery of the NAS. The table is based on information provided by NAS-suppliers and NAS-users (shaded blue).

	Time required for		
System	Mobilisation	Deployment	Recovery
BBC-HTL	1 week, 4-6 months	3 hours	3 hours
BBC-Weyres	2 days to 2 weeks	2 hours	1 hour
BBC-users	1-6 months	1-2 hours, 12-16 hours	1-2 hours, 12-16 hours
NMS	1 day to 1 year	30 mins	30 mins
NMS-users	Depends on availability, can be 2 years for larger piles	1 hour	1 hour
HydroNAS	8 weeks	30 mins	30 mins
HSD	2-3 months	4 min/ 10 m water depth	4 min/ 10 m water depth
HSD-users	1-6 months	< 30 mins-1 hour	< 30 mins-1 hour
AdBm-NAS	3 months	10 mins	10 mins
BLUE Hammer	Up to 12 months	0	0
VH-Cape Holland	1-12 months for up to 6 m diameter piles, 18 months for new built, 1-5 days from port to vessel deck	0	0
VH-PVE	Minimum 3 days from port to vessel deck	0	0

8.3.2.1 Bubble Curtains

The deployment and recovery times of BBCs are provided in Table 12, and the specifications given by the NAS-suppliers are generally in good agreement with those of the NAS-users. The 12 – 16 hour deployment and recovery time is stated by a NAS-user and is explained by the fact that a window of 12 hours for a single BBC between two pile-installations is often requested by the BBC-team (16 hours for a double big bubble curtain (DBBC)) to ensure a suitable weather window and tide conditions. While the BBC is best deployed before the installation vessel is at the piling position, the recovery of the BBC must be coordinated with the installation vessel (NAS-user). In general, no delay should be expected for the installation work by the application of a BBC (Table 13), as it is deployed from an auxiliary vessel and can be deployed before the installation vessel arrives. Also, a sequential deployment of multiple systems is possible, i.e., early deployment of the next nozzle hose whereas another one is already used (NAS-user). Usually, the preparation, deployment and recovery of a BBC is optimised to minimise any delay, however, if changes in the installation sequence occur, or weather conditions are unsuitable, additional coordination needs to be considered when using a BBC (NAS user). Delays in the pile installation may occur if the weather window is unsuitable for BBC deployment (BBC user, see also section 8.4.2). One NAS-user stated additional time from zero to 2 hours for preparation and deployment, respectively, and zero to 1.5 hours for recovery.

8.3.2.2 Casings

The deployment and recovery of the casings is done from the installation vessel. Deployment/recovery times are provided in Table 12, and expected delays in the piling process are provided in Table 13. Since the NMS is also the installer, it is difficult to distinguish between “normal” erection time and “additional” time needed due to noise reduction related work. This can explain the different views of NAS-user and NAS-supplier. IHC IQIP points out that the NMS reduces the time for pile placement. This is because the NMS is combined with a monopile installer, keeping the pile in place during installation.

Table 13. Additional time that will or may incur for the piling process of a foundation due to the on-site preparation (prep), deployment (depl), operation (op) and recovery (rec) of the NAS. The table is based on information provided by NAS-suppliers and NAS-users (shaded blue).

	Additional time (min)				
System	prep	depl	op	rec	Note
BBC-HTL	0	0	0	0	If the BBC is deployed in pre-lay
BBC-Weyres	0	0	0	0	
BBC-user	0-120	0-120	0	0-90	
NMS	0	30-45	0	30-45	The NMS reduces time for pile placement
NMS-user	15	30	10	30	
HydroNAS	15-30	15-30	15-30	15-30	The project details may cause some variance in these timings
HSD	0	0	0	0	No additional time delay
HSD-user	30-90	30-90	0-30	30-60	HSD-j user
AdBm-NAS	30-60	10-15	0	5-15	Many of these answers depend on the deployment methodology, which can change significantly
BLUE Hammer	<15	0	0	0	Handling time identical to conventional hammer
Vibro-CAPE Holland	0	0	0	0	Time likely reduced as processes are skipped
Vibro-PVE	0	0	0	0	

8.3.2.3 Resonators

Like the casings, resonators can be deployed and recovered within 1 hour, respectively (Table 12). While OffNoise Solution states that no delay is expected in the piling process when using their system, the user of the HSD-j for the jacket foundation experienced delays (Table 13), which may be due to the use of a system, for which less experience exists. One NAS-user reported experiencing difficulties where the NMS had “sunk” into the scour protection during installation, making the retrieval more difficult.

8.3.2.4 Alternative hammers

The BLUE Hammer and VH replace the conventional hammer, and accordingly, no delay in the piling process should be expected according to the NAS-suppliers (Table 12, Table 13). NAS-users, however, point out, that the BLUE Hammer needs to be filled with sea water which may lead to delay in the piling process, which takes, according to the NAS-supplier, less than 15 minutes (Table 13). Delays may also occur when changing between the VH and the conventional impact hammer. CAPE Holland offers a Vibro Lifting Tool, a certified lifting tool combined with the VH, that can be used to pick up a stored pile, upend it and lift it to the installation position and start driving straight away in a single operation. This also means fewer movements, resulting in time saving during installation. According to CAPE Holland, the time savings can be significant even in the cases where an impact hammer is required for the final blows; using the lifting tool with a VH, a much smaller vessel with an impact hammer could be used after pile installation.

8.3.3 Deck requirements, dimensions and consumables

8.3.3.1 Bubble curtains

As a BBC is deployed from an auxiliary vessel, the deck requirements of these systems are independent from the installation vessel facilities, and they do not use up deck space that otherwise would be used for piles and other installation equipment. The auxiliary vessel, however, needs to offer sufficient deck space for the compressors. In Germany, the maximum number of compressors for the operation of a BBC is restricted to 22 by the consenting authorities to restrict fuel consumption (Boethling, pers. comm.), therefore the maximum deck space specified by the BBC-suppliers in Table 14 is likely for 22 compressors. According to one NAS-user, dynamic positioning (DP2 mode) is also needed, to hold the vessel in place during BBC deployment. BBC deployment does not require a crane (and ultimately no modification of the pile gripper). The hose is coiled on a drum and is de-coiled during deployment (NAS-user). One BBC-user noted that a crane is needed for loading and unloading the compressors and drums.

Table 15 provides information on the system’s weight, and if the system and auxiliary equipment fit in standard containers, which would simplify on-board storage. There is some discrepancy between the BBC-supplier HTL and the BBC-user as to whether the system and auxiliary equipment fit in a standard container. The fuel consumption per piling operation depends on the number of compressors used within an OWF-project and the length of the BBC-deployment (which depends on the piling operation). The number of compressors depends on the size and design of the BBC (if used in single, double or triple configuration), which in turn depends on the efficacy needed for an OWF-project and water depth (see also section 8.6). A difference to note between the compressors of the two BBC-suppliers is that the HTL-compressors are oil-free, while the compressors used by Weyres are not – they use oil-filters to remove the oil from the compressed air (Koschinski, pers. comm.). Fuel is also needed for the auxiliary vessel and for the dynamic positioning (NAS-user).

8.3.3.2 Casings

The NMS is a rigid and, compared to the other systems (Table 15), heavy shell system that requires a crane of sufficient lifting capacity (Table 14). Due to its dimensions, it cannot be stored in standard containers. The length of the NMS needs to be sufficient for the water depth it will be operated in, which will also determine the crane’s lifting height (NAS-user). The pile gripper is included in the monopile installer entailing the NMS. The system requires a hydraulic power pack and air compressors for the optional bubble curtain entailed in the system, and operation of the NMS is connected to fuel consumption (Table 15).

The HydroNAS is built of a telescopic rubber sleeve that can be folded and therefore can fit into standard containers (Table 15). It is much lighter than the NMS and therefore has less demand on the crane for deployment (Table 14). It may need a modification of the pile gripper for deployment. The HydroNAS will be filled with 150 m³ of air to establish a sound barrier, and therefore needs a compressor.

Table 14. Deck requirements of the NAS. The table is based on information provided by the NAS-suppliers and NAS-users (shaded blue). N/A = supplier/user stated that question is not applicable, - = no information given by supplier/user.

System	Crane: lifting Capacity (tons)	Crane: lifting Height (m)	Deck space (m²)	Pile gripper Modification	Pile gripper Automatic release
BBC-HTL	-	-	400- 800	No	N/A
BBC-Weyres	-	-	600- 800	No	N/A
BBC-user	- 2*	- 5*	400-600 Depends on # compressors	No	N/A
NMS	800	80	160	No	N/A
NMS-user	Depends on water depth and pile diameter More than for monopile itself			-	-
HydroNAS	200	60	65	Yes	Yes**
HSD	-	-	-	Yes	Yes***
HSD-user	3.5 Less than a pile	5	15-30 (HSD-j)	Yes	Yes
AdBm-NAS	10****	4	0	May be needed	Yes
BLUE Hammer	700	Pile height + 30	200-250	No	N/A
VH-Cape Holland	Depending on pile weight	Appr. 10	500 for MP	No	N/A
VH-PVE	Depends	N/A	depends	No	N/A

* Requirements for loading and unloading the compressors and drums
** The deployment can have a sleeve/ ballast which can be set inside the pile gripper
*** Hanging below the pile gripper, lowered with winches
**** Depending on deployment method it sometimes needs main crane

Table 15. Dimensions and consumables of the NAS-systems in review. The table is based on information provided by the NAS-suppliers and NAS-users (shaded blue). - = no information given by supplier/user.

System	Weight (t)	Fit into standard container: System	Fit into standard container: Auxiliary equipment	Consumables per piling operation
BBC-HTL	8	Yes	Yes	1,800 l fuel 100 l / compressor / hour fuel
BBC-Weyres	28	No	No	40 l / compressor / hour fuel
BBC-user	-	No (BBC-HTL)	No (BBC-HTL)	Depends on # compressors ca 80-90 l / compressor Fuel for DP2 vessel
NMS	800	No	No	420 l fuel
NMS-user	Depends on water depth and pile diameter	No	-	-
HydroNAS	30	Yes	-	150 m³ air fill per deployment
HSD	25-70	No	Yes	None
HSD-user	4	Yes	No/yes	Electricity for winches
AdBm-NAS	10	Yes	-	Electricity/hydraulic winches are used to deploy the system
BLUE Hammer	700	No	Yes	Fuel 2000 l diesel,
VH-Cape Holland	200-500	No	No	200-1000 l fuel
VH-PVE	depends	No	No	Fuel

8.3.3.3 Resonators

The resonator systems are lightweight systems in comparison to the NMS and alternative hammers, but similar to the BBC and HydroNAS (Table 15). They use comparably little or no deck space (Table 14). The HSD is generally placed in the ballast basket fixed to the pile gripper. The AdBm-NAS is also designed to sit underneath the pile gripper, or it can be mounted to the side of the vessel during travel. The HSD and AdBm-NAS are lowered with winches. The AdBm-NAS-supplier states that sometimes the main crane may be needed depending on the deployment method. This might be the same for the HSD, given that some NAS-users stated crane lifting capacity and height (Table 14). A specific frame/gripper would be needed for the HSD for pin piles (NAS-user). Modifications of the pile gripper may also be needed for the AdBm-NAS (Table 14).

8.3.3.4 Alternative hammers

The dimensions of the BLUE Hammer (see Figure 7) are much larger than those of a conventional impact pile-driver. Therefore, assuming that the BLUE Hammer stands upright and entirely replaces the conventional hammer, some additional deck space is needed. One NAS-user highlighted that the BLUE Hammer may not work for all installation vessels due to its requirements. Additional deck space may also need to be considered for the VH hammer, in cases where an additional impact hammer is needed alongside the VH to install the pile (see section 8.2.4). One NAS-user commented that additional deck space may be required to store a back-up system; this is dependent on the wind farm developer's risk mitigation strategy. Deck requirements are provided in Table 14 and dimensions and consumables in Table 15. A conventional impact pile driver needs a power pack which requires deck space and also uses diesel for which a tank must be provided (which may be inside the power block) (Koschinski, pers. comm.).

Table 16. Number of staff needed for deployment of the NAS. The table is based on information provided by the NAS-suppliers and NAS-users on who provides the staff: the EPC/EPCI-contractor, the OWF-developer or the NAS-supplier and NAS-users (shaded blue). - = no information given by supplier/user.

	Deployer/Operator			
System	EPC/EPCI	OWF	NAS	Number of staff
BBC-HTL			x	2 shifts with 3 mechanics each
BBC-Weyres			x	3
BBC-user	x	x	x	BBC-supply vessel crew + minimum 2 staff of NAS-supplier, minimum 3 up to 10 staff
NMS	x		x	1, same as hammer staff
NMS-user	x		x	Most likely installation contractor Part of installation team + additional staff
HydroNAS		x	x	2 per shift
HSD	x	x		No additional staff
HSD-user	x		x	2-5, most likely installation contractor
AdBm-NAS	x	x	x	1 (no additional staff needed)
BLUE-hammer	x			1-3
VH-Cape Holland	x			3
VH-PVE	x			2

8.3.4 Deployment crew

8.3.4.1 Bubble curtains

The deployment of BBC is usually carried out by the BBC-supplier (NAS-supplier), but according to the NAS-users, also the EPC/EPCI-contractors[19] (most likely) or OWF-developer may be responsible for deployment (Table 16). The staff requirements needed to deploy a system are provided in Table 16.

8.3.4.2 Casings

As the NMS is part of a monopile installation system, the deployment is done by the staff operating the hammer, but additional staff may be needed (Table 16). Other than what is stated by the NAS-supplier (Table 16), nothing more can be said for the HydroNAS, as offshore-experience is lacking.

8.3.4.3 Resonators

The application of the HSD is most likely done by the installation team, as the HSD is linked to the pile gripper. While the NAS-user state that up to 5 staff members are needed for the deployment, the NAS-supplier specifies that no additional staff are needed (Table 16). This is not necessarily a contradiction, as the staff members deploying the HSD and installing the pile may be the same people. Like with the HydroNAS, offshore-experience is missing for the AdBm-NAS (other than that currently gained through the recent offshore tests mentioned in section 4).

8.3.4.4 Alternative hammers

The alternative hammers are operated by the EPC/EPCI-contractor and the number of staff is likely the same as needed to run a conventional hammer (Table 16).

[19] EPC/EPCI-contractor: the contractor responsible for the Engineering, Procurement and Construction (and Installation) of the wind farm.

Table 17. Percentage of malfunctions expected during an OWF-project with 80 foundations when using the NAS (expressed as percentage of foundations piled without or with limited noise mitigation). The table presents information provided by the NAS-suppliers and NAS-users (shaded blue) and is based on their experience. N/A = supplier/user stated that question is not applicable, - = no information given by supplier/user.

			Time needed to	
System	Malfunction	Mitigation	Repair	Replace
BBC-HTL	0	None	0.5 h (on deck)	1 d*
BBC-Weyres	0	Spare winch incl. hoses and power pack	0.5 h (on deck), Otherwise *	0.5 h (when mitigation in place), otherwise *
BBC-user	Range: 0-9 % Mainly: 1-4 %	Additional BBC, short term repair	Hours to days	Hours to weeks
NMS	0	An air compressor as spare	2 h	-
NMS-user	0-4 %		3 days	weeks
HydroNAS	1-4 %	Have a full back up system available	12 h**	
HSD	0 – 4 %	Spare net - backup system	-	3-4 h***
HSD-user	0 – 4 % 5-9 % (HDS-j)	Spare net	Days to weeks	One to several weeks
AdBm-NAS	0	Operational malfunction: system can be lifted in its fully deployed state over pile. Acoustic malfunction: elements can be modified and vertical spacing can be altered to increase concentration of acoustic elements.	We haven't encountered this yet	
BLUE Hammer	1-4 %	Spare parts, replacement components	hours	-
VH-Cape Holland	0	Spare parts, preventative maintenance	Really depends on the breakdown and contingency the customer has chosen	
VH-PVE	0	N/A	-	-

* Depends mainly on the distance between OWF and harbour
** This would be a concurrent activity while the back-up is in use
*** Replacement of backup system at the quay

8.3.5 Malfunction

The percentage of malfunctions of the specific NAS (expressed as percentage of foundations piled without or with limited noise mitigation), assuming an OWF-project with 80 foundations, are provided in Table 17. For those NAS for which user information is available, the time for repair and replacement reported by users is generally higher than the time predicted by the NAS-supplier. It was generally noted that it is hard to predict the time needed for repair, as it very much depends on the reason why a NAS is not functioning. Bellmann *et al*. (2018) reports that for 450 NMS and 340 HSD uses, malfunctions were reported less than 1% of the time. Some issues can be solved quickly while others will need a longer period to be solved (NAS-users). Major issues, however, could lead to considerable delays in the installation schedule, if the regulatory regime does not allow piling to continue without the NAS being in place. One NAS-user pointed out that one consequence of a system malfunction during operation may be a decrease of the noise reduction efficacy.

Having a back-up system in place is the most common solution for avoiding any major delays with most NAS (Table 17). Due to its deck-space requirement, it is, however, not feasible to have a spare NMS on board. Here, a restart of the system often helps (NAS-user).

8.3.6 Health, safety and environment

Table 18 lists which (if any) Health, Safety and Environment (HSE) requirements should, according to the NAS-suppliers, be additionally considered when working with the NAS included in this review. Each operation will be carefully risk assessed but the use of NAS may lead to an increase in the overall levels of risk as a result of the additional staff, equipment, processes and, in some instances, vessels that need to be considered in the operation. The Risk Assessments and Method Statements (RAMS) should cover all these risks.

Table 18. Additional health, safety and environment (HSE) requirements to be considered, according to the NAS-suppliers and NAS-users (shaded blue) for the use of their NAS-system.

System	HSE
BBC-HTL	None
BBC-Weyres	None
BBC-user	Working on open deck during equipment operation
NMS	Working at heights
NMS-user	Additional heavy lifting actions
HydroNAS	Lifting, working at height, working near pressurised gas
HSD	None
HSD-user	Risk of entanglement
AdBm-NAS	None
BLUE Hammer	Risk of potential pile run*: verification that the weight of the hammer can be taken by crane, otherwise it must be decoupled from the crane hook to prevent severe damage to the installation vessel.
VH-Cape Holland	None
VH-PVE	None

* A ‘pile run’ means a rapid fall of the pile which may occur in cases where extremely soft soil layers and/or cavities are encountered during installation.

8.4 Environmental factors limiting NAS deployment and operation

8.4.1 Water depth

Table 19 provides an overview of the operational limitations of the NAS with regard to water depth, according to the NAS-suppliers, and the water depth ranges in which the NAS-users reported using the NAS systems.

The question in the questionnaire regarding the water depth in which the NAS was commercially deployed, was not specifically restricted to OWF. The BBC-supplier Weyres and both VH-suppliers reported commercial deployment of their systems in non-OWF projects in water depths > 70 m. Weyres applied their BBC 70 times at one project (Nord Stream 2) during UXO clearance in water depths up to 90 m. With regard to OWF-projects, the OWF Veja Mate is one of the deepest wind farms in Germany. According to Weyres, the deployment of their BBC during pile installation at Veja Mate was at water depths up to 46 m. Bellmann *et al*. (2018) specify that, during OWF construction, HSD and BBC were used in water depths up to 45 m, and that BBCs were used in waters up to 70 m for UXO clearance.

The deepest German OWF at which VH (from PVE[20]) was used is OWF Global Tech 1, with a water depth up to 40 m. CAPE-Holland specified that their VH was used to install OWF monopiles in the North Sea in water depths up to 30 m. VH are regularly used by the Oil and Gas industry for jacket pin piles (as reported by one NAS-user). CAPE-Holland reported that they have used VH for pre-piling of jackets in water depths up to 90 m in the North Sea off the coast of Aberdeen, Scotland[21]. This was a non-OWF project, but according to CAPE-Holland, this installation procedure is in principle the same as for an OWF project.

IHC-IQIP confirmed that their NMS has been commercially deployed in water depths up to 45 m. They pointed out that the NMS can be extended for its use in water depths up to 50 m. They stated that they can generally offer a system for any water depth at which a monopile can be installed.

Given that BBC, HSD and NMS were deployed in OWF projects up to ~45 m, and VH in OWF projects up to 40 m, for the purpose of relating the information provided in Table 19 to the prevailing water depths at the potential OWF sites in Scottish waters, the maximum water depth for a commercial deployment in OWF projects was set to 40 m (VH) and 45 m (BBC, HSD and NMS) (Table 20). The commercial deployment of BBC and VH in non-OWF projects at water depth > 70 m was also considered in this evaluation.

BBC and VH are the only NAS that have been commercially deployed in the range of water depths that can be found at the Scottish OWF sites (Table 20). According to one NAS-user, deployment and efficacy of BBC system is more challenging in waters deeper than 30 m and even though it has been commercially deployed at these depths, it resulted in a number of challenges due to the increased hydrostatic pressure and increased compression of air at depth to ensure that sufficient air gets from surface compressors to the hoses lying on the seabed. A larger number of compressors and a higher operating pressure are needed for deeper water to generate a higher air flow to ensure that large enough bubbles are released into the water at depth (Koschinski, pers. comm.).

Table 19. Water depth at which the NAS under review can be deployed and successfully operated. The table is based on information provided by the NAS-suppliers and NAS-users (shaded blue). - = no information given by supplier/user.

	Water depth			
			Commercially deployed	
System	In theory	Field proven	OWF projects	Non-OWF projects
BBC-HTL	> 70 m	> 70 m	to 40 m	
BBC-Weyres	> 70 m	> 70 m	to 50 m	> 70 m (UXO)
BBC-user	> 70 m	to 50 m	to 50 m	
NMS	to 50 m	to 50 m	to 50 m	
NMS-user	> 70 m	to 50 m	to 50 m	
HydroNAS	> 70m	10 to 20 m	-	
HSD	50 to > 70 m	to 50 m	20 to 50 m	
HSD-user	> 70m	to 50 m	up to 50 m	
AdBm-NAS	> 70m	to 40 m	-	
BLUE Hammer	> 70m	to 30 m	-	
VH-Cape Holland	-	-	to 30 m	> 70 m (O&G)
VH-PVE	> 70 m	> 70 m	to 40 m	> 70 m (O&G)

[20] https://offshore.pve-holland.com/content/665/Wind-farms/Wind-farm-projects/
[21] https://www.offshore-technology.com/projects/culzean-gas-field-north-sea/

From the remaining NAS, only the NMS and HSD have been commercially deployed at water depths prevailing in the shallow parts (≤ 45 m) of some of the Scottish OWF sites (Table 20). Of the HSD, the noise reducing elements need to be adapted to the static pressure of the water depths to ensure a sufficient efficacy. The NMS is, according to the supplier, extendable for the use in water depth up to 50 m. A model that could be used in water depths deeper than 50 m is currently not available, which makes the NMS currently unsuitable for most Scottish OWF sites. However, the NMS-supplier stated that they can tailor a system to any monopile that is to be installed in deeper waters. The variation in water depth across a construction site can cause difficulties when applying a NMS. One NAS-user explained that the height of the shield must be adapted to the water depth of the piling position to ensure that the shield's top is above water level at high tide while ensuring sufficient lifting height remains on the vessel to lift the monopile into the shield. The height of the shield can be amended (to some extent) to the varying water depth within a construction site, but this takes time.

The range of water depths that can be covered by an NMS depends on the lifting height of the installation vessel in use: the higher the lifting height that can be covered by the crane on the construction vessel, the larger the range of depths across a site that can be covered by the NMS. Having two shields of different lengths on board the installation vessel to cover a larger range of water depths is not an option, as each unit takes up so much deck space that only one unit can be stored on the vessel (NAS-user). According to the NMS-supplier, the application of the NMS is restricted in cases where the water depth between piling positions varies more than 10 m. In some of the Scottish OWF sites, the water depth varies more than 10 m (see Table 7).

However, the final decision of the foundation locations and their respective depth range, as well as the lifting height of the installation vessel's crane will determine the suitability of an NMS. The NAS-user that had experience with the HDS-j also pointed out restrictions for HSD-use with regard to water depth variation: the length of net that can be kept in the basket is not infinite and only accommodates a certain water depth. When the water depth is shallower than the maximum water depth it accommodates for, some of the net remains on top of the water line, which could cause entanglement with the hammer. The limit for the water depth range for an HSD was given by this user as 15 m. The resonators (HSD and AdBm-NAS), the HydroNAS and the BLUE Hammer are, in theory, suitable for all water depths prevailing in the Scottish OWF sites.

Of all Scottish OWF sites, only the existing OWF Robin Rigg at 7 to 13 m water depth is within the depth range where all NAS seem to be suitable and have been at least field proven (Table 20).

Table 20. Theoretical applicability of NAS in the Scottish OWF sites based on the water depth of the sites provided in Table 7 and information detailed in the current section and by the NAS-suppliers in Table 19. Which NAS can potentially be deployed is indicated according to the key provided below the table. Commercially available NAS are bolded.

Region	OWF #	Water depth (m)		**BBC**	**NMS**	**HSD**	AdBm-NAS	Hydro NAS	BLUE Hammer	**VH**
NE	2	Min	39	✓	✓	✓	(✓)	*	*	✓
		Mean	45	✓	✓	✓	*	*	*	o
		Max	53	o	x	*	*	*	*	o
	3	Min	40	✓	✓	✓	(✓)	*	*	✓
		Mean	48	o	*	(✓)	*	*	*	o
		Max	57	o	x	*	*	*	*	o
	8	Min	49	o	*	(✓)	*	*	*	o
		Mean	53	o	x	*	*	*	*	o
		Max	58	o	x	*	*	*	*	o
E	4	Min	47	o	*	(✓)	*	*	*	o
		Mean	52	o	x	*	*	*	*	o
		Max	57	o	x	*	*	*	*	o
	5	Min	50	o	*	(✓)	*	*	*	o
		Mean	54	o	x	*	*	*	*	o
		Max	58	o	x	*	*	*	*	o
	6	Min	42	✓	✓	✓	*	*	*	o
		Mean	49	o	*	(✓)	*	*	*	o
		Max	54	o	x	*	*	*	*	o
	7	Min	46	o	*	(✓)	*	*	*	o
		Mean	51	o	x	*	*	*	*	o
		Max	54	o	x	*	*	*	*	o
	9	Min	50	o	*	(✓)	*	*	*	o
		Mean	56	o	x	*	*	*	*	o
		Max	63	o	x	*	*	*	*	o
SW	1	Min	7	✓	✓	✓	(✓)	(✓)	(✓)	✓
		Mean	10	✓	✓	✓	(✓)	(✓)	(✓)	✓
		Max	13	✓	✓	✓	(✓)	(✓)	(✓)	✓
W	10	Min	19	✓	✓	✓	(✓)	(✓)	(✓)	✓
		Mean	47	o	*	(✓)	*	*	*	o
		Max	77	o	x	*	*	*	*	o

Key	Deployment at prevailing water depth
x	Cannot be deployed
*	In theory possible
(✓)	Field proven
✓	Commercially deployed in OWF-projects
o	Commercially deployed in non-OWF-projects

8.4.2 Metocean parameters

The environmental limitations for deployment and operation of the NAS as reported by the NAS-suppliers and users are provided in Table 21. NAS-users reported more conservative environmental limits with regard to wave height for BBC, NMS and HSD, and for the BBC also with regard to wind speed, than the NAS-suppliers. One NAS-user mentioned that for BBC and NMS, a significant wave height (Hs) of 1.5 m is the frequent limiting factor for safe deployment and operation, and that suppliers often tend to overestimate the wave height limits. It was also noted that wave height usually limits the NAS-use before wind speed does. However, the NMS is reported to be robust to weather conditions (NAS-user).

Environmental limits were provided for all NAS except for the alternative hammers, for which, according to the NAS-suppliers, the limits are determined by the installation vessel (Table 21). The ability of the installation vessels to operate (jack-up barges, dedicated wind turbine installation vessels or heavy lift vessels (Crol, 2015, Paterson *et al*., 2018)), will be determined by the significant wave height, wind speed and current speed. Their operational limits depend on the individual operations that need to be conducted. According to one NAS-user, each operation will be risk assessed for the specifics of the site and operations and appropriate limits determined based on the identified risks. An estimate of the operational limits of installation vessels for the installation of foundations is provided in Table 22 (an estimate given by Paterson *et al*. (2018) and Chenu *et al*. (2016), along with examples of operational limits for installation vessels during jack-up operations or lifting as required during foundation installation).

Chenu *et al*. (2016) noted that it is important to have the widest weather window for the vessel to ensure good availability and install the maximum number of OWF foundations in a period of time. The use of NAS other than alternative hammers may reduce the weather window in those cases in which the metocean limits for deployment and operation are below those of the vessel's operational limits for foundation installation. In those cases, where the operational limits of a NAS match or are above those of the vessel, the installation vessel will be the limiting factor with regard to metocean conditions. It is therefore important to consider the operational limits of the installation vessels together with the limiting conditions of a NAS.

Given that, according to questionnaire responses, the limiting significant wave height for most of the NAS, except alternative hammers, ranges from 1.5 to 3 m (Table 21), the use of NAS, where their limits are below those of the installation vessel, may influence the weather window for foundation installation for OWFs in the regions Northeast, East and West of Scotland in all seasons except summer (Table 9).

The upper wind speed limits for those NAS, where this information was given, range from 10 to 20 m/s (Table 21), therefore the use of NAS (except alternative hammers) may be a limiting factor in autumn for the OWFs in the Eastern and Western region, and in winter for OWFs in all regions but the Southwest. For OWFs in the Southwest, only the current speed seems to be a limiting factor and only during spring tide when it is above 1 m/s (Table 7), as the deployment and operation limits with regard to current speed for the NAS, excluding alternative hammers, ranges from 1 to 3 m/s (Table 21).

Table 21. Environmental limitations of the NAS for deployment (depl) and operation (op) with regard to wind speed, significant wave height and current speed. The table is based on information provided by the NAS-suppliers and NAS-users (shaded blue). - = no information given by supplier/user.

	Wind speed (@10m)		Significant Wave height (m)		Speed currents (m/s)		
System	depl	op	depl	op	depl	op	Reason / comment
BBC-HTL	14	20	2	3	1	1	Handling during deployment
BBC-Weyres	-	-	3	3	3	3	Limits given from vessel
BBC-user	10-13	10-13	1.5-2	1.5-2	-	-	Similar to installation limits Wave height limiting before wind speed
NMS	Crane limitation	Crane limitation	2	2	1	1	
NMS-user	-	-	1.5	1.5-2	-	-	Wave height limiting before wind speed
HydroNAS	15*	-	3	-	1**	-	The system stability in current and wind conditions will require careful control and management
HSD	-	-	-	2.5	-	2.5	May be higher, to be considered individually for each design
HSD-user	-	15	-	1-1.5	-	-	For HSD-j only
AdBm-NAS	-	-	4	4	3	3	Concerns regarding pile coating damage due to system interactions with pile
BLUE Hammer VH-CAPE Holland VH-PVE	Limitations determined by installation vessel						

* Control by the use of tag lines/winches
** Reasonably large area presented to the tidal current

Table 22. *Reported operational limits for installation vessels during foundation installation.*

Vessel (Company)	Operation	Operational limits: Significant wave height (m)	Wind speed (m/s)	Current (m/s)	Source
Aeolus (Van Oord)	Jack-up operations	3.6	20	1.54	Crol (2015)
Oleg Strashnov (SHL)	Lifting	2.5	17	1	Wassink
Estimate for installation vessel used for UK round 1 & 2	Foundation installation	2	12	Not stated	Paterson *et al.* (2018)
Estimate based on various vessels	Foundation installation	2	20	Not stated	Chenu *et al.* (2016)

With regard to the water current, the best option for operating a BBC, as mentioned by one NAS-user, is the slack tide, to avoid drifting of the bubbles. However, this would often not be viable in an OWF-project. Rising air bubbles will drift with the current, causing gaps in the 'curtain' enclosing the pile, thereby affecting the efficacy of a bubble curtain (Nehls *et al.*, 2007). With a rise velocity of 0.3 m/s, (realistic for a BBC) and a tidal current of 1 m/s, bubbles would drift off by about 70 m when rising from 20 m depth to the water surface. Thus, the resulting bubble curtain would not build up vertically but obliquely. Therefore, to provide a complete shield, the BBC would need to be deployed in an oval shape, with the point of the oval ring greater than 70 m away from the pile position facing the current (Figure 10). The distance to the pile should be increased with increasing water depth and should also be increased linearly with increasing current speed. The efficacy of the BBC is impacted by strong currents, especially in deeper waters (NAS-user).

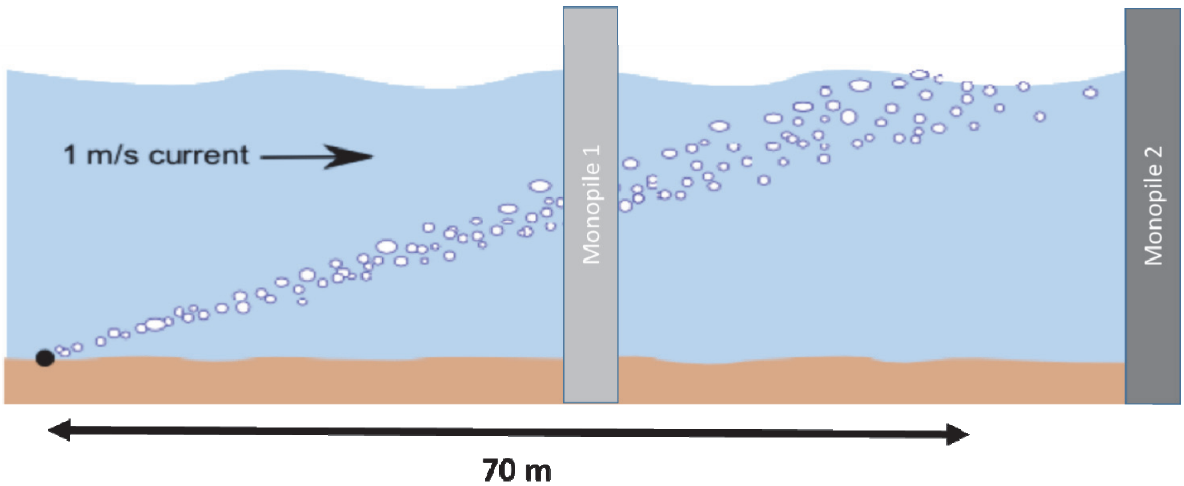

Figure 10. Rise of bubble curtain in a current speed of 1 m/s. The bubbles (white dots) arising from a nozzle hose (black dot at sea floor) drift with the current, so that the resulting curtain is oblique, and bubbles reach the water surface after 70 m of horizontal drift, (assuming a water depth of ~20 m). Monopile 1, situated closer to the nozzle hose, will not be sufficiently shielded by the curtain, while monopile 2, situated further than 70 m from the nozzle hose, will be shielded over the whole vertical range of the water column by the bubble curtain. Adapted from Nehls et al. (2007).

Soil geology does not seem to limit the application of a BBC, according to both BBC-suppliers and users. The only comment was that large sand waves and ripples in the deployment area may challenge the deployment, although this had not been experienced in any actual project of the specific BBC-user. The same comment was also provided in relation to the NMS. According to the supplier, the NMS needs a special deployment measure for soft substrate surface layers, although no further details on the nature of this measure were provided. One NAS-user specified that the NMS would sink into the surface layer during deployment on soft substrate, which would explain the requirement for special measures when deploying in such surfaces. Hard surface layers reduce the noise reduction efficacy of the NMS due to ground coupling effects (see also section 8.6.1), which will be the same for the HSD. For the HSD, the ballast box may sink into the ground on soft substrate (NAS-user). The HydroNAS-supplier said that their system will require a mud mat on soft soil to stabilise the system to prevent it from sinking. For all hammer types, hard substrate was stated by the corresponding suppliers as a limiting factor. Further comments by the supplier were that rock cannot be penetrated by VH, and may create refusal with the BLUE Hammer. This might, however, also be an issue with a conventional hammer. Very dense sand should, however, according to one of the VH-supplier, not be an issue.

8.5 Cost implications of using NAS

The main cost drivers for the NAS, according to NAS-suppliers and users, are provided in Table 23. Respondents were also asked to provide an estimate for rental costs for a NAS used in a hypothetical OWF project in UK waters with 80 foundations being installed within a 12-month period. These estimates are provided in Table 24.

Table 23. Main cost drivers for the use of the NAS under review. The table is based on information provided by the NAS- suppliers and NAS-users (shaded blue).

System	Modifications	Extra offshore time	System rental costs	Vessel costs	Not sure	Other
BBC-HTL				x		Compressors
BBC-Weyres				x		
BBC-user		x	x	x		
NMS			x			
NMS-user	x	x	x	x		
HydroNAS			x			Mobilisation and demobilisation if significant re-work is required
HSD	x					Construction of ballast box; purchase price of HSD-nets
HSD-user	x	x	x			
AdBm-NAS			x			
BLUE Hammer			x			Costs do not increase, BLUE hammer replaces conventional hammer
VH-CAPE Holland			x			The system is likely to save costs in the installation process due to the combination of pile handling and driving
VH-PVE					x	

Table 24. Rental costs and services included for an assumed OWF with 80 foundations in UK waters as estimated by the NAS-suppliers and NAS-users (shaded blue). For the rent estimate of the NAS-user, the time frame, for which they completed the questionnaire, is also given. - = no information given by supplier/user.

	Rental costs per OWF						Included						
System	<€5m	€5 to €10m	€10 to €15m	>€15m	confidential	not stated	Personnel	Auxiliary vessel	Consumables	Auxiliary equipment	Energy supply	Not sure	Time frame
BBC-HTL	x						x	x	x	x	x		
BBC-Weyres	x						x	x	x	x	x		
BBC-user				x			x	x	x	x	x		2012-2014*
				x			x	x	x	x	x		<2012
		x	x				x	x		x			2015-2017
		x					x	x	x	x	x		2015-2017**
						x	x	x	x	x			<2012 to >2017
NMS-IHC					x		x			x	x		
NMS-user				x									2012-2014*
				x									2015-2017
HydroNAS-W3G	x						x		x	x			
HSD-OffNoise	x								-				
HSD-user	x	x					x		x				2015-2017**
		x					x						2015-2017***
						x			x				<2012 to >2017
UNAS-AdBm	x						x		x	x			
BLUE-Fistuca							x		x	x	x		
Vibro-CAPE Holland	x						x		x	x			
Vibro-Dieseko	x											x	

* From NAS-user who gave information on concurrent use of BBC and NMS
** From NAS-user who gave information on concurrent use of BBC and HSD
*** From NAS-user who gave information on HSD-j

One NAS-user stated that costs may vary, as project-specific adaptations would be required (e.g., number of vessels, water depth, noise limits that may need to be considered). This may explain the variation in the cost estimates given by the NAS-users for the BBC and HSD. Costs for the BBC may increase with an increasing number of compressors and length of nozzle hose, which may be needed for deep waters and/or high noise reduction efficacy. Costs for the HSD will increase with increasing number and/or lengths of HSD-nets needed.

The experience of NAS-users is mainly from projects in German waters, in which piling noise is required to be below an SEL_{ss} threshold value of 160 dB re 1 µPa²s @ 750 m and $L_{pk,\ flat}$

threshold value of 190 dB re 1 µPa @ 750 m. Based on recent experience with monopiles of 8 m diameter, noise reduction of up to 20 dB has been required to keep the SEL_{ss} below the threshold (Bellmann *et al.*, 2018). In the German OWF projects, mostly double BBC have been applied (Philipp, 2018), which results in higher rental costs, due to (amongst others) an increased number of compressors needed to run two BBC rings instead of one. Philipp (2018) states that from 2014 to 2018, the costs for NAS ranged between € 6m and € 25m per project, with reference to the OWF-projects provided in Table 1. These costs include the use of concurrently deployed NAS as none of the projects used solely a single BBC, NMS or HSD. The costs in 2014 to 2018 are lower compared to the NAS costs in 2011 to 2014, which ranged from € 15m to € 36m (Philipp, 2018). This may explain the higher cost estimates for a BBC given by those NAS-users sharing their experience of the years up to 2014 compared to those providing information for the time frame of 2015 to 2017. It has to be noted that, for the NAS-users that completed questionnaires for two concurrently used systems, it is not clear whether the costs given are based on the use of two different NAS or for one system only. Specific feed-back from one of these users was, that it was difficult to specifically provide answers for one system only when they had only had prior experience with two concurrently deployed systems.

While most NAS can be rented, the HSD-nets have to be purchased, and each net will last for around 30 to 40 pile installations. After this level of use, the foam elements fatigue and need to be replaced. OffNoise Solutions take back all used HSD-nets for recycling. Costs for a net depend on its size, deployment depth and configuration and start at € 500,000 per net. Steel-ware for the HSD (ballast box and winches under the gripper) has to be manufactured by the installation company, and costs for manufacturing were estimated by OffNoise Solution to be around € 500 - 700,000. The steel-ware, once built, is then part of the installation vessel and can be re-used. According to this information, the direct costs for using an HSD in the hypothetical Scottish 80 foundation wind farm would therefore not exceed € 5m, excluding staff.

AdBm can rent out either a system that includes the steel framework that holds the resonators or just the resonators themselves. They mentioned that most installation contractors have specific needs for their vessel and project, so the deployment system is a non-standard piece of equipment. For this reason, the resonator-only option seems to be the most popular option. Purchases can be made at a higher cost but come with an annual maintenance agreement to ensure the system stays in good condition. Prices are not yet finalised, but AdBm states that they would definitely be lower than those for the NMS and likely less than those for the HSD system. The AdBm-NAS should have an indefinite lifespan if used and maintained properly, as the system uses air, which always returns to its original volume and does not fatigue.

CAPE-Holland reported that the use of their VH system would reduce installation process costs due to the combination of pile handling and driving. However, a full replacement of the conventional hammer by the VH may currently not be an option, as long as the uncertainties with regard to drivability and bearing capacity of piles installed with a VH are not resolved (see section 8.2.4).

8.6 Noise reduction efficacy

8.6.1 Reduction in sound levels

The Institute of Technical and Applied Physics, itap GmbH, have conducted most of the noise measurements during OWF-construction in German waters, doing so in compliance with national and international noise measurement standards. They therefore have a good overview of the noise reduction efficacy of NAS. Bellmann (pers. comm.) from itap GmbH is currently preparing a technical report on behalf of BSH on the lessons learnt from the application of noise mitigation systems, including updated results on noise reduction efficacy. This report is anticipated to be available in 2019.

Bellmann *et al*. (2018) provides information on the noise reduction efficacy of BBC, NMS and HSD for the installation of piles at or below 40 m water depth (which is the shallower end of the water depth expected at the Scottish potential OWF-sites, Table 7). At such sites, a reduction in SEL_{ss} of 7 to 18 dB can potentially be achieved when using a BBC, NMS or HSD (Table 25). While the minimum values of the BBC and DBBC shown in Table 25 are based on measurements in the early years of deployments, the last two years have shown that a noise reduction of at least 10 dB can be guaranteed for all three systems (BBC, HSD and NMS) (Bellmann, pers. Comm). Bellmann *et al*. (2018) point out that the efficacy can be increased by using a combination of NAS (e.g., BBC and NMS, or BBC and HSD), however, the resulting reduction in SEL_{ss} would be lower than the sum of each single reduction (Table 25). They note that the reduction in $L_{pk,\, flat}$ is similar to or greater than the reduction in SEL_{ss}.

While the efficacy of the BBC increases with increasing air volume flow (Table 25), the efficacy of a BBC, deployed with the same configuration, decreases with increasing deployment depth (Bellmann, pers. Comm), primarily caused by the increase in hydrostatic pressure as discussed in section 8.4.1. The NMS seems to be 1 to 6 dB more effective than the HSD (Table 25). However, the efficacy of NMS and HSD also depends on their configuration (see section 8.6.2). Due to the placement of the NMS and HSD close to, and directly around the pile, these systems shield the noise radiated from the pile into the water column. IHC states that 99 % of the sound energy propagated directly from the pile into the water column is mitigated by the NMS. There are, however, two more transmission paths for the sound generated by the impact of the hammer on the pile: from the pile into the soil, and from the soil into the water (Lippert, 2018, Figure 11). This sound is called ground borne noise, and the effect is referred to as ground coupling. The efficacy of NAS deployed directly around the pile is therefore influenced by the soil geology as sound gets bent in non-homogeneous soil (layers of different soil types). Sound reflected by the soil back into the sea can be mitigated by systems deployed at further distance from the pile, however currently only the BBC can achieve this.

In contrast to the systems outlined above, results of the noise reduction efficacy during full deployment of the NAS around a piling location are not available for the AdBm-NAS and the HydroNAS. For both systems, demonstration tests were conducted during pile-driving events, for which the results are presented by the suppliers in Coplen (2014) for the AdBm-NAS, and W3G Marine Ltd (2015b) for the HydroNAS. Both projects demonstrated that piling noise is, in principle, attenuated by the systems. While a full-scale test of the AdBm-NAS has been recently conducted, and it is anticipated that results will be publicly available in 2019 (Wochner, pers. comm.), no full-scale tests have been conducted yet for the HydroNAS (Giles, pers. comm.).

Fistuca presented the first results of their BLUE Pilot full scale offshore test at a conference in Berlin (Winkes 2018) and provided further details for this report (Figure 12). The test was conducted in a water depth of 22 m with a pile of 6.5 m diameter and 60 m length. The results were compared to published results of driving a pile of 4 m diameter and 54 m pile length with a hydraulic hammer in another project (OWF Q7 (Princess Amalia, the Netherlands)) that occurred in the same area as the BLUE Pilot project. They also included the results of a third project (OWF GEMINI, the Netherlands) where a pile of 6.6 m diameter and 63.4 m length was driven into the seabed at 30 m water depth. The comparison indicates a 19 to 24 dB reduction in SEL_{ss} (Figure 12).

*Table 25. Minimum and maximum noise reduction efficacy of single BBC or DBBC applied with different air volume flow (given in m³/(min*m), NMS, HSD and combined systems in German OWF-projects with pile sites at given water depths. From Bellmann et al. (2018).*

NAS	Water depth	Noise reduction Δ SEL_{ss} (dB)
$BBC_{(>0.3m^3/(min*m))}$	~ 40 m	7 - 11
$DBBC_{(>0.3m^3/(min*m))}$	~ 40 m	8 - 13
$DBBC_{(>0.4m^3/(min*m))}$	~ 40 m	12 - 18
$DBBC_{(>0.5m^3/(min*m))}$	> 40 m	~ 15-16 (based on 1 pile)
NMS	Up to 40 m	13 - 16
HSD	Up to 40 m	10 - 12
NMS + optimised $BBC_{(>0.4m^3/(min*m))}$	~ 40 m	17-18
NMS + optimised $BBC_{(>0.5m^3/(min*m))}$	~ 40 m	18-20
HSD + optimised $BBC_{(>0.4m^3/(min*m))}$	~ 30 m	15-20
HSD + optimised $DBBC_{(0.48m^3/(min*m))}$	20-40 m	15-28
HSD + optimised $DBBC_{(> 0.5m^3/(min*m))}$	< 45 m	18-19

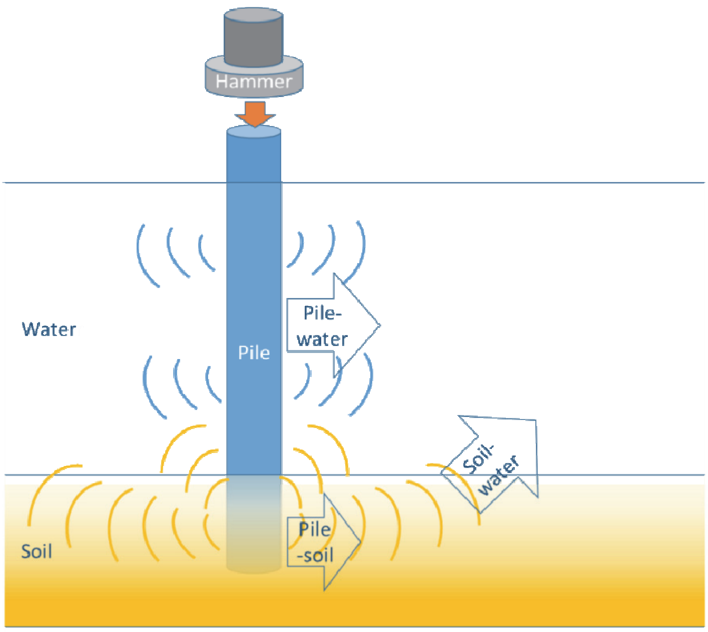

Figure 11. Pathways of piling sound into the water. Three sound transmission pathways exist: (1) from the pile directly into the sea (through vibration of the pile), (2) from the pile to the soil, and (3) from the soil into the sea (through vibration of the soil). Adapted from Lippert (2018).

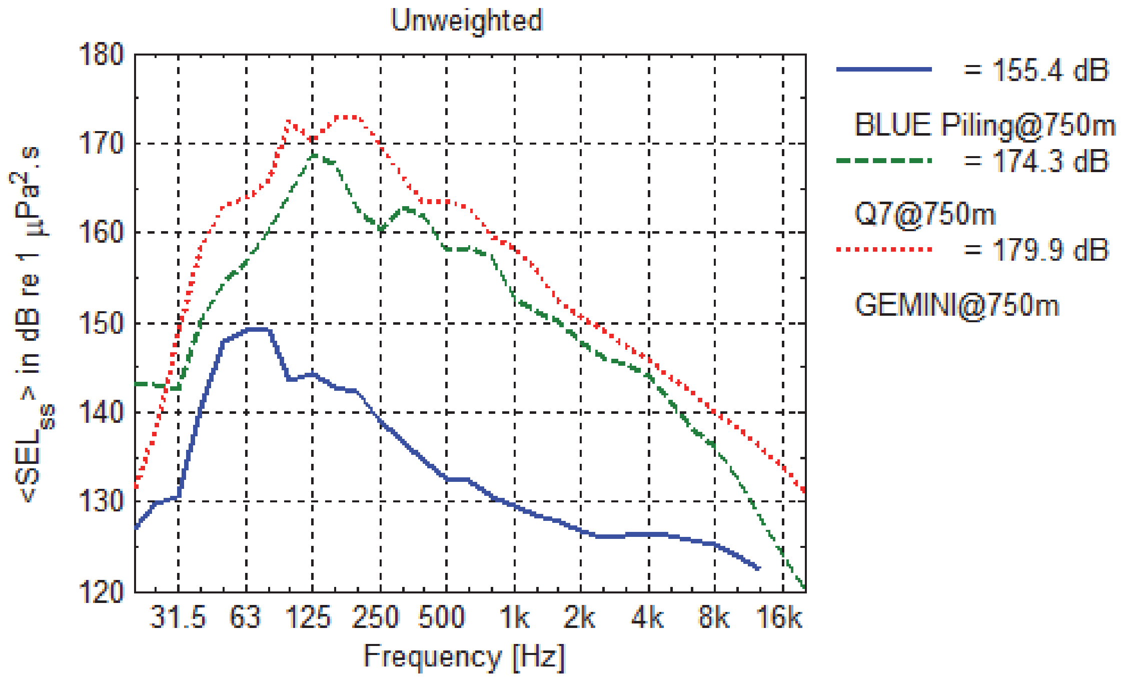

Figure 12. First results of the BLUE Pilot study, showing a comparison of the pile strike frequency spectrum of a BLUE hammer (blue line) in comparison with spectra of pile strikes with a conventional hammer at project Q7 and GEMINI. © TNO, Fistuca.

The noise emission of a VH cannot directly be compared to that of a hammer strike. While pile strikes result in a series of broadband pulses, VH emit tonal continuous sound. However, calculations based on field measurements indicate a 15 to 20 dB lower noise emission for VH compared to impact piling (Elmer *et al*., 2007, Betke and Matuschek, 2011). Examples of absolute sound levels for VH during wind farm construction can be found in Thomsen and Verfuss (in press).

8.6.2 Frequency dependent reduction

The noise reduction efficacy of BBC, NMS, HSD and BLUE Hammer is better above 100 Hz than below 100 Hz (e.g., Figure 13, Figure 14). The efficacy increases with increasing frequency for BBC and NMS, and is more or less flat for the frequency range of 100 Hz to 2 kHz for the BLUE hammer. It has to be noted that these results are based on only a few examples, and noise reduction efficacy will vary from site to site, and depend on a variety of circumstances (e.g., background noise conditions, the system configuration, and distance to pile position). At the OWF DanTysk, for example, noise levels at > 8 km were reduced down to ambient noise from 1 kHz upward by a BBC (Figure 15). An estimate of the noise reduction at higher frequencies would in this case lead to an underestimate. The NAS-user Weyres state that the frequency dependent efficacy can be controlled with the help of the distances between nozzle holes and the amount of compressed air. Nehls *et al*. (2007) point out that the resonance frequency of the BBC's air bubbles is dependent on their size, leading to a frequency dependent absorption that could be regulated by adjusting the air bubble size. We are, however, unaware that this is applied in practice, and HTL states that the frequency range that their BBC covers cannot be controlled. It will be difficult to control bubble size over the whole water column as bubbles split in a chaotic way during their rise and with decreasing hydrostatic pressure (Koschinski, pers. comm.).

According to the suppliers, the HSD and the AdBm-NAS are systems that, in theory, can be tuned to a certain frequency range. A numerical simulation of the frequency-dependent effectiveness and the ability to tune the HSD, validated with data measured during the

ESRA-project, are published in Elmer *et al*. (2011) and Elmer (2013). Lake experiments with tethered encapsulated bubbles (resonators) to inform the efficacy of the AdBm-NAS showed that the frequency spectrum of the attenuated sound varies with the size of the resonators (Lee *et al*., 2017). The studies for both systems showed that the resonance frequency of the resonating elements (the frequency at which most of the sound energy is reduced) increases with decreasing size of the resonator. The suppliers explained how the systems can be tuned as follows: the HSD can be adapted and tuned to specific frequencies by varying the size and number of foam and gas-filled rubber elements, considering the hydrostatic pressure. The acoustic elements of the AdBm-NAS can be controlled by adapting their size and considering the water depth (hydrostatic pressure) they will be deployed at. Any spectrum can be targeted with advance notice of the desired range. The resonance frequency can, according to the supplier, easily be modified which will cause peak attenuation at the resonance frequency and approximately 10 times above.

With the NMS and HydroNAS, the frequency range of noise reduction cannot be controlled. According to W3G, best reduction with the HydroNAS is reached above 500 Hz. The BLUE Hammer is also not tuneable to a specific frequency range.

The frequency spectrum of the noise emitted by VH has tonal components with fundamental frequencies usually between 20 to 40 Hz plus harmonics. Above 500 Hz the spectrum is even and can extend to several kHz (Spence *et al*., 2007). CAPE-Holland stated that the frequency of their VH can be varied between 20 and 23.3 Hz. Compared to the frequency range of impact piling noise, sound levels in the 100 Hz to 1 kHz frequency range are significantly less for VH noise (Betke and Matuschek, 2011).

According to the data available for this review, the NAS are more effective with regard to mitigating noise impact on marine mammals and fish with a swim bladder (see also section 6.3) than on fish without a swim bladder (although a reduction of > 5 dB in SEL at 50 Hz can be achieved with the BBC, NMS, HSD and BLUE Hammer, see Figure 13 and Figure 14). The HSD and AdBm-NAS may be configurable to achieve a suitable reduction in the low frequency range concerning fish without a swim bladder, however this has yet to be tested. The application of a BLUE Hammer reduces sound across the whole frequency range beyond 50 Hz (Figure 14) and is therefore effective for all marine mammals and fish with a swim bladder. NMS and BBC may reduce the noise more efficiently at higher frequencies, which impact high frequency cetaceans, compared to the BLUE Hammer (Figure 14), but will also mitigate sound affecting other marine mammal species and fish with a swim bladder.

The effectiveness of using a VH to reduce the risk of auditory impact on marine mammals can, at a first glance, be judged as high, as the sound levels at frequencies above 50 Hz are significantly lower than those occurring during conventional impact piling. Additionally, continuous sound is less harmful than impulsive sound with regard to auditory injury. However, the total noise energy received by an animal is important to consider when assessing the risk of auditory injury; a fleeing animal will receive noise energy (of decreasing levels) continuously from a VH, and only bouts of noise energy from impact piling with silent periods in-between pile strikes. An assessment of the auditory impact ranges would need to be carried out to get a better understanding of this matter. With regard to the potential impact on the behaviour of the animal, it is not clear whether the lower sound levels of VH compared to conventional impact piling consequently lead to a reduced behavioural impact, as the characteristics of the VH noise are different to that of the impact pile. VH noise may elicit a different behavioural reaction in marine mammals compared to impact piling, even at lower noise levels. Graham *et al*. (2017) suggest that a better understanding of the behavioural responses to vibropiling is needed before recommending its use to mitigate impact piling.

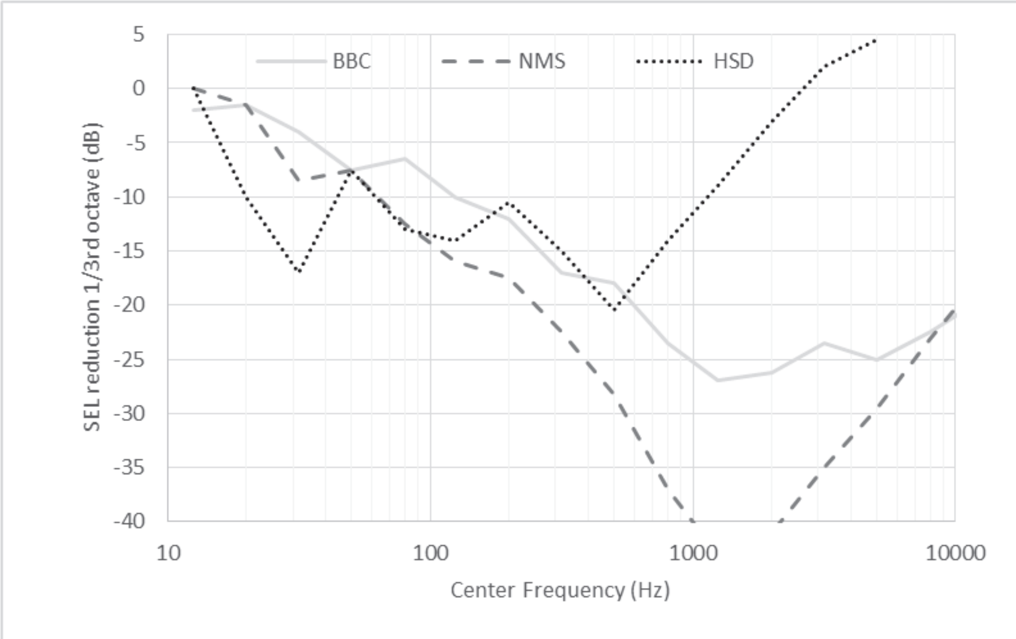

Figure 13. Reduction of the 1/3rd octave band frequency spectrum of a pile strike when comparing mitigated versus unmitigated piling. The reduction achieved by a single BBC at OWF Borkum West II, NMS 6500 (several wind farms) and HSD at OWF Amrumbank West are shown. Adapted from information kindly provided by Bellmann, itap GmbH.

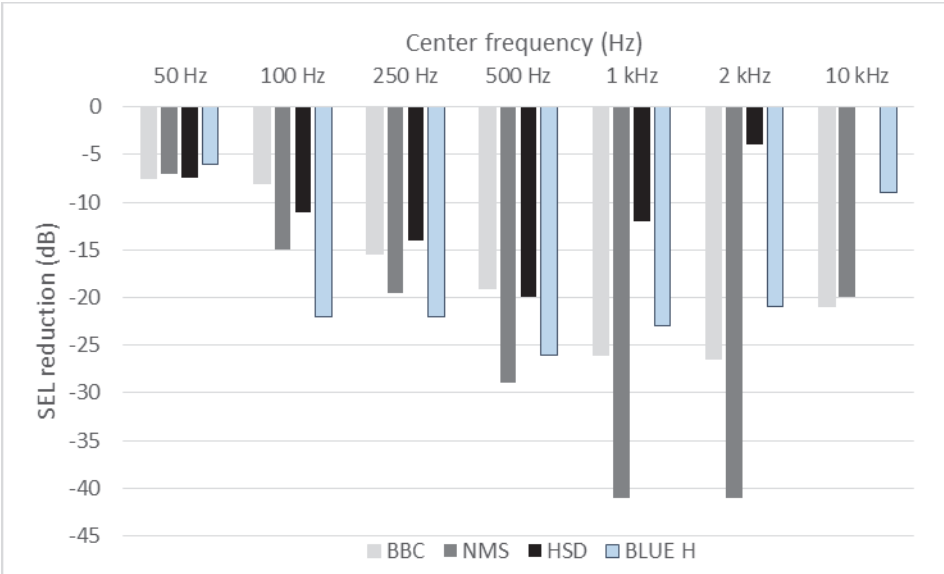

Figure 14. Reduction in SEL at the frequencies 100 Hz, 250 Hz, 500 Hz, 1 kHz and 2 kHz in the 1/3rd octave band frequency spectrum of a pile strike when comparing mitigated versus unmitigated piling. Values for BBC, NMS and HSD are taken from Figure 13, values for the BLUE Hammer are taken from Figure 12, comparing the frequency spectrum of the BLUE Hammer with that obtained at Q7.

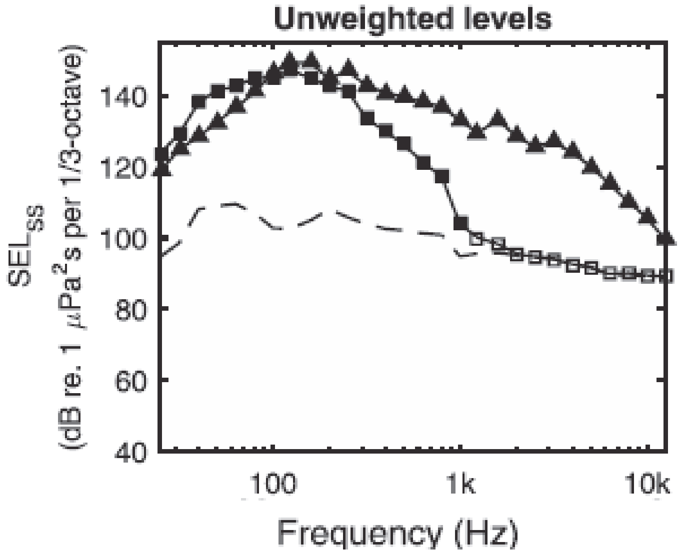

Figure 15. Frequency spectra of pile strikes at the OWF farm DanTysk for unmitigated piling (triangles) and mitigated piling (squares) by means of a BBC. Ambient noise levels are also shown (dashed line). Note that piling noise is mitigated to ambient noise levels for frequencies above 1 kHz (white squares). Measurements were taken at 8.1 km (unmitigated) and 8.8 km (mitigated) distance from the pile position. From Tougaard and Dähne (2017).

8.6.3 Factors influencing the effectiveness

The following technical factors were highlighted by the NAS-suppliers and users to affect the efficacy of a NAS. The environmental factors limiting the NAS deployment and operation (see section 8.4) are the same as those influencing their effectiveness and are therefore not repeated here.

Technical factors affecting the effectiveness of a BBC are the air volume pumped into the nozzle hose, the hose length, the configuration of the nozzles (e.g., distance between nozzles) and the nozzle hole size (NAS-supplier and NAS-user). The examples in Table 25 show that the configuration of the BBC (single or double) and the air volume stream used to run the system have a clear effect on the noise reduction efficacy. One NAS-user reported that the way a hose is ballasted affects its efficacy. It was also reported by a NAS-user that nozzle holes may become clogged after longer term pre-deployment of the hose if air pressure is not applied. Due to this, the deployment time of a DBBC in Germany is restricted by the German authorities (BSH) to a maximum of five days (Philipp, 2018).

One NAS-user reported that the distance between the inner and outer shell of the system can affect the efficacy of an NMS. The NAS-supplier commented that the use of the integrated confined bubble curtain of the NMS increases the efficacy of the system. There are different NMS systems available which have slightly different options for how to set up the system, which affects the efficacy.

Technical factors affecting the efficacy of an HSD are the size and quality, allocation and material of the noise mitigating HSD-elements (NAS-supplier, NAS-user). The design of the ballast box is also important as one needs to ensure that it does not emit any underwater noise, i.e., there is no contact to vibrating structures such as the pile (NAS-user).

As for the HSD, for the AdBm-NAS, the size and concentration of acoustic elements affect noise reduction efficacy. The concentration has a direct effect on the total amount of reduction as more acoustic elements result in a better acoustic attenuation. The size affects the frequency that is most attenuated at a particular water depth.

No technical factors were given by the NAS-supplier for the HydroNAS that would affect its efficacy.

9. COST/BENEFIT REVIEW

Systems to reduce noise during OWF pile driving have, to our knowledge, so far not been used in Scottish waters. The range of NAS that are currently commercially available and potentially suitable in all relevant water depths of Scottish waters are the BBC, HSD and VH. The HSD and BBC can reduce the broadband SEL_{ss} of piling noise by at least 10 dB. Rental costs are likely to start somewhere below € 5m for an 80 turbine OWF-project. However, direct costs of these systems will increase with increasing demands on the noise reduction and environmental challenges (such as increasing water depth).

Indirect costs for applying a NAS are also important to consider but are difficult to estimate as they are likely to vary on a case by case basis. These may be minimal in fair weather conditions and when deployment and recovery is managed by an experienced team, but can be considerable e.g., higher vessel costs due to increased offshore time needed for the NAS operation, larger weather windows that are needed and/or lower operational limits for pile installation which may negatively influence the installation schedule, delays which are caused by NAS-malfunctions and repair times, and the need for increased transport-transit effort due to reduced deck space on board of the installation vessel. Philipp (2018) reported that each day of delay for the installation spread costs between € 250,000 and € 350,000, plus lost revenue and additional costs caused by knock-on effects. Furthermore, the use of additional staff, equipment, processes and potentially vessels will lead to an overall increase in complexity and risk that needs to be considered in any risk assessment.

Only the BBC and VH have proven track records for deployment in water depths that are typical across future Scottish OWF sites, although the existing experience at depths over 45 m is not from OWF-projects. Still, the challenge for the BBC remains that the installation and effectiveness is affected by water depth and current speed. For the VH, uncertainties with regard to drivability and bearing capacity, as well as the effect of the different quality of noise emission on marine wildlife remain to be considered. For the NMS, a new model would need to be built that is applicable in water depths deeper than 50 m, but, according to IHC IQIP, any water depth at which a monopile can be installed, should be feasible to build an NMS for. The AdBm, HydroNAS and the BLUE Hammer have the potential to be used in these waters, but either field experience is missing, or the technology is still to be fully validated.

Alongside the review of the effectiveness of a NAS, the introduction of other impacts (e.g., additional fuel consumption, increased waste) should be evaluated and minimised where feasible.

All systems reduce, some at least in theory, the noise emission of impact piling, or emit lower noise levels than those emitted during conventional impact piling. The effectiveness of a BBC depends on its configuration. The HSD seems to be generally less effective than the NMS and BLUE Hammer with regard to the reduction of broadband noise levels (Table 25), the full-scale demonstration of the effectiveness of the AdBm-NAS is still confidential, and the effectiveness of HydroNAS has yet to be demonstrated at full-scale. The VH certainly emits lower noise levels, however, introduces a different noise type, for which the impact yet has to be assessed. The efficiency of a NAS to reduce the likelihood of auditory injury in marine animals depends on the frequency range at which sound energy is reduced and on the target species, as each species is sensitive to a specific frequency range. The NAS that have been proven at full-scale (BBC, HSD, NMS and BLUE Hammer) reduce the sound exposure level of a single strike at 50 Hz by 6 to 7 dB, which is the frequency that fish and LF cetaceans are particularly sensitive to. The efficacy increases with increasing frequency, which makes the systems suitable for all marine mammals and fish sensitive to higher frequencies. The NMS and BBC are the most effective NAS in the higher frequency range (e.g., at 10 kHz), which makes these systems especially effective in reducing impact to high frequency cetaceans, such as the harbour porpoise. HSD and AdBm-NAS may, in theory, be tuneable to reduce noise in specific frequency ranges and may therefore be tailored to the specific needs of a target species.

10. SUITABILITY OF NOISE ABATEMENT SYSTEMS FOR USE DURING CONTROLLED EXPLOSIONS OF UNEXPLODED ORDNANCE

After the First and Second World Wars, a huge amount of munitions were dumped at designated sites or randomly into the sea. Also numerous items of live ammunition introduced into the sea during combat operations have not yet been cleared. These munitions represent a risk to fishermen, divers, other professional and recreational users of coasts and sea as well as marine species (OSPAR, 2010). Clearance of these UXO is required where they pose a risk to industrial offshore activities. Clearance often involves on-site detonation which entails a high risk, not only to the clearance team, but also to the surrounding marine life, as underwater explosions are one of the strongest noise sources found in the sea (Richardson, 1995). Explosions result not only in the emission of sound (compression) waves but produce also a shock wave: the explosive material transforms into a gas bubble upon detonation with a propagation speed much faster than sound, resulting in a shock wave (Richardson, 1995). With regard to marine mammals, concerns have been raised as the detonation of UXO may lead to death or physical injury in the near vicinity, and auditory injury or behavioural impact at larger ranges (e.g., von Benda-Beckmann *et al.*, 2015a, Koschinski, 2011). von Benda-Beckmann *et al*. (2015a) estimated, that in the Dutch continental shelf alone, the 88 explosions that occurred during one year in 2010/2011 for UXO clearance, potentially caused 1,280, and possibly even up to 5,450, permanent hearing loss events in harbour porpoise. PTS-impact ranges were in the order of one to several kilometres, and possibly further for larger explosions.

Koschinski and Kock (2009) present potential alternative techniques to clear UXO without the need for blasting, which comprise of freezing, the use of robotic equipment, water abrasive suspension cutting, disposal in a static detonation chamber and photolytic destruction of explosive substances. Currently, researchers of the German Fraunhofer Institute in cooperation with salvage companies are developing a semi-automated robotic disposal system in the project RoBEMM, (robotic underwater salvage and disposal process for the disassembly of ammunition in the sea). This aims at making detonations of large munitions items such as mines and water bombs obsolete in the near future (Eitner and Tröster, 2018).

Of the NAS presented in this review, the BBC, HSD and AdBm-NAS were reported by the NAS-suppliers as a potential mitigation tool during UXO clearance. Only bubble curtains have so far been tested and used in the field for such purpose (as detailed below), and AdBm-NAS tested in tank trials with a combustive sound source, used to simulate UXO noise (Wochner *et al*., 2017a).

The German Federal Armed Forces Underwater Acoustics and Marine Geophysics Research Institute (FWG) conducted a series of controlled tests to understand the efficacy of bubble curtains as a noise mitigation tool during mine explosions in 2008 (Schmidtke *et al*., 2009), 2010 (Schmidtke, 2010), 2011 and 2012 (Schmidtke, 2012). In 2008, Schmidtke *et al*. laid three concentric semicircle bubble curtains (7.5 to 11.5 m) around a detonation site in the German Baltic Sea, with the semicircle opening towards the coast line. They tested the difference in noise reduction when using one to three bubble curtains with a constant airflow of 20 m^3/min when detonating 1 kg charges at 13 m water depth. The resulting attenuation was more than 10 dB and up to 16 dB in peak sound pressure levels, with the DBBC giving the best results. In a second test, they detonated a standard mine of 300 kg explosive with 45% TNT at 20 m water depth with one bubble curtain circle of 22 m diameter around the detonation site, resulting in a 4 dB reduction in peak pressures. Schmidtke *et al*. (2009) explained the lower efficacy of the bubble curtain for larger charges compared to the smaller charges as follows: larger charges in mines contain ingredients that produce much more gas than expected for TNT. The flow of the displaced water caused by the expanding gas bubble from the detonation constitutes a significant part of the pressure, which is a low frequency effect that cannot be dampened by the bubble curtain. They suggested enlarging the diameter of the bubble curtain circle to supress the effect of the displaced water flow, which they have then tested at 70 m in their experiments in 2010 (see next paragraph).

Schmidtke (2010) increased the radius of the bubble curtain to 70 m in their experiments, testing a bubble curtain semicircle open to the coast line near Kiel in the German Baltic Sea. Detonating a 300 kg mine at a water depth of 12 m, they achieved a noise reduction of 16 to 19 dB in peak sound pressure levels for two explosions, with an air volume flow of the bubble curtain of 1 m^3/min/m. During a third explosion, technical issues with the bubble curtain resulted in a reduction of its efficacy to 6 dB attenuation of the peak sound pressure levels.

In 2011, Schmidtke (2012) investigated the influence of the air volume flow on the efficacy of the semicircle bubble curtain with 70 m radius. The attenuation of the peak sound pressure level of 20 g test explosives was 24 dB on average, regardless of volume of air flow (0.5 or 1.0 m^3/min/m). The explosion of a 300 kg mine, however, only achieved a 6 dB reduction in peak sound pressure level. This is because, in these later experiments, continual detonation had resulted in a crater developing around the detonation site. This meant that the crater caused an acoustic shadow between the detonation site and the hydrophone.

Grimsbo and Kvadsheim (2018) measured the noise levels of four 500 kg TNT detonations at a military test site between Bergen and Stavanger and investigated the effectiveness of a bubble curtain, which was implemented to protect an aquaculture facility 6 km away from the detonation location. The bubble curtain was deployed approximately half way between the detonation location and aquaculture facility at a water depth up to 30 m. They recorded 6.2 dB to 12.4 dB lower peak sound pressure levels compared to the unmitigated detonation. No details on the air volume flow were provided.

The bubble curtain of Weyres was deployed 70 times in water depths up to 90 m during UXO-clearance for the Nord Stream 2 gas pipeline project[22] in the Baltic Sea (Kloske, pers. comm.). Meriläinen *et al*. (2018)[23] details the results of the underwater noise monitoring of UXO clearances in the Finnish EEZ during this project. In this part of the Baltic Sea, UXO were found in water depth up to 88 m (Kloske, pers. comm.). Bubble curtains had to be used for munitions with a total explosive charge + donor charge of 22 kg or more and for the clearance of all munitions east of an area that was not further specified. 58 out of 74 munitions were cleared with the use of a BBC to mitigate noise (Meriläinen *et al*., 2018). Noise measurements of the clearances showed that all but one measured peak pressure levels were lower than assessed in the permit application, however, no evaluation of the effectiveness of the bubble curtain was presented.

Field applications, such as those conducted by Schmidtke and team in very shallow waters, and by Grimsbo and Kvadsheim (2018) at water depth up to 30 m, prove the bubble curtain to be a useful noise mitigation tool for UXO clearance. Schmidtke *et al*. (2009) and Schmidtke (2010) present the frequency spectrum of the mitigated detonation noise. A detailed discussion of the frequency dependent attenuation is, however, out of the scope of this review.

Parameters influencing the effectiveness of bubble curtains are already described in section 7.5.3 of this report, and it is likely that effectiveness for UXO detonation will vary in relation to these parameters in a similar way.

[22] https://www.nord-stream2.com/
[23] Used with kind permission of Nord Stream 2 and kindly provided by Bodac B.V.

The use of bubble curtains as a mitigation-tool for larger explosions is also recommended by von Benda-Beckmann *et al*. (2015b), as these systems are commercially available and have been shown to reduce peak sound pressure levels. However, they highlight that extra time is required for setting up the system, as well as an extra vessel for the compressors. Another issue is the risk of the proximity of the system and the vessel to the explosives while deploying the bubble curtain, and the likelihood of damage to the bubble curtain system during detonation, in addition to the relative high costs for the use of the system (von Benda-Beckmann *et al*., 2015b).

von Benda-Beckmann *et al*. (2015a) also rated, based on views expressed at an expert workshop, the potential effectiveness of the use of shielding and resonant air-filled spheres (such as the AdBm-NAS) as high. The practical issues for the use of this system were noted as the same as for the bubble curtain, apart from the need for compressors. While the AdBm-NAS has been successfully tested in full-scale for pile driving (see section 3), the applicability of it for mitigating explosive sound pressures has so far only been successfully tested in a tank with a combustive sound source (Wochner *et al*., 2017a, Wochner *et al*., 2017b). AdBm state that they can either offer a system that is reusable or disposable. A reusable system will need to be large enough not to be destroyed, and that size will vary based on the charge weight and type of explosive of the munition. If a system only needs to be used once, it can be damaged or destroyed during detonation. The system can then be made much smaller and would be constructed from magnesium alloys which corrode back into seawater in a short period of time.

HSD-nets can, in theory, also be used for UXO-clearance. An application of the nets similar to that of purse-seine netting might be conceivable in order to build a large circle around the ammunition site. This, however, has to be investigated further.

It is important to note that any of the NAS mentioned above will only reduce the noise impact but cannot prevent harmful substances from entering the environment due to incomplete combustion of explosives, especially during low-order detonations (Koschinski, 2011). The scale of contamination by explosions needs further investigation. Another point to consider is that a 6 dB reduction in peak sound pressure level will reduce the radius, within which the level is above a given threshold, by around half (as a minimum), and the corresponding area by about 75%.

11. CONCLUSION

The survey revealed that two kinds of NAS have so far been applied in water depths found in potential future Scottish OWF-sites and are commercially available: the BBC and the VH. These systems have been used in OWF-projects in water depths up to 45 m (the deepest water depth OWFs in Germany are currently built in). Deeper commercial applications were for UXO clearance (BBC, up to 90 m) and Oil and Gas projects (VH) (e.g., pre-piling of jackets up to 90 m). Both systems have some uncertainties associated with them: while being considered by German authorities as a state-of-the-art system for water depths up to 40 m, the application of BBCs in waters deeper than 40 m may remain challenging due to the need for an increasing number of compressors to form a suitable bubble curtain at higher hydrostatic pressures, and to counteract against the drift of the bubbles on their path to the water surface. The VH is currently mostly used in connection with a conventional piling hammer, which at least retains some impact caused by this conventional method (although over a shorter period of time). Also, the VH emits a different kind of noise that may need further assessment to ensure that this method indeed reduces the impact on marine animals.

The use of resonators may also be a potential solution for use in Scottish waters, but field experience is lacking in waters deeper than 45 m, with monopiles of diameters greater than ~8 m, and with the installation of jacket foundations. Only the HSD is currently commercially available and considered by German authorities as state-of-the-art for water depths up to 40 m (used for monopile installations). The AdBm-NAS may be a potential option for future applications, but field experience remains scarce.

Casings are currently not a solution for Scottish waters with water depths deeper than 50 m, as NMS-models are currently only available for shallower waters, and only for monopiles. HydroNAS may be a potential option for future applications, but field experience is still lacking.

The BLUE Hammer may also be a future option; however, proven field demonstration is also lacking for this system.

While the information gained through the review can give an indication of the suitability of the different NAS and the challenges that might be encountered at the various potential future OWF-sites, a detailed and project specific evaluation would need to be undertaken to evaluate feasibility on a project by project basis. This project specific evaluation should take into account factors such as the local environmental conditions at the OWF-site, the required degree of noise reduction and the specification of the potential installation vessels available at that time.

Direct costs of the application of NAS during construction can only be estimated once the required degree of noise reduction is known as well as evaluation of the local environmental conditions that influence the noise reduction efficacy of the NAS. In addition, the current market demand will also influence costs at any specific time. One current issue raised by NAS-users is that only a few BBC suppliers and one supplier of a resonator (HSD) and a casing (NMS), respectively, are currently offering NAS (with proven records).

Due to the experience gained in German waters throughout the past decade, the risk for indirect costs due to time delays and malfunctions is now much less than a decade ago when deploying one of the commonly used systems in water depths up to 40 m. The limited experience in waters deeper than 40 m, however, brings challenges that have rarely been faced by NAS-suppliers and users to date. Time delays may still occur in seasons and areas in which the weather conditions are unfavourable and in cases where larger installation vessels are used with operational weather limits above those limiting the use of certain NAS.

The application of BBC with strong currents might also be challenging especially when it comes to deeper waters. Increased demands on the configuration of the BBC in deeper waters and/or those with strong currents may also increase costs.

With the BBC, NMS and HSD, broadband sound levels can be reduced by a at least 10 dB (for both, $L_{pk, flat}$ and SEL_{ss}) and reductions have been demonstrated of up to 20 dB and more for the SEL when combining two NAS. The BLUE Hammer resulted in a noise reduction of around 20 dB in SEL_{ss} in its first full-scale trial, with the caveat that full validation of the technology is still pending. The NAS are generally more effective at reducing the risk of noise impact on marine mammals and fish sensitive to higher frequencies than for fish that are only sensitive to frequencies below 100 Hz.

With regard to UXO-clearance, only the BBC has been proven to reduce the impact ranges caused by explosions, and, although BBCs have been applied during UXO clearance in water depths up to 90 m, the efficacy of these systems has only been investigated in water depths up to 30 m. AdBm-NAS and HSD are a potential option for UXO-mitigation but would need further investigation.

12. DATA GAPS AND RECOMMENDATIONS

This review revealed the following knowledge gaps and uncertainties:

- Lack of experience with commercial deployment of NAS in OWF-projects in waters deeper than 45 m,
- Lack of field experience with NAS other than BBC and VH in waters deeper than 45 m,
- Lack of field experience with NAS for piles with a diameter greater than ~8 m,
- Lack of field experience with NMS and little experience with HSD applied during the installation of jacket foundations,
- Lack of experience with serial- and commercial deployment of BLUE Hammer and AdBm-NAS in OWF-projects, and outcomes of full-scale tests yet not published,
- Lack of full-scale tests with HydroNAS followed by serial- and commercial deployment,
- Lack of noise impact assessment of VH noise,
- Perceived risks regarding drivability of piles to be installed with VH due to little experience with the use of VH in OWF-projects,
- Diverging opinions regarding the need to assess the axial bearing capacity of monopiles driven with VH, and
- Lack of full knowledge on drivability and bearing capacity of piles driven with BLUE Hammer.

Filling these data gaps will lead to a better understanding of the applicability of the NAS systems in Scottish waters.

Project-specific assessment should be conducted to ensure the most suitable NAS option and configuration is chosen, fitting the environmental conditions of the corresponding OWF-site, and the specification of the installation vessel.

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14. ANNEX 1: QUESTIONNAIRE

SMRU Consulting

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Questionnaire on Noise Abatement Systems

This questionnaire is aimed at stakeholders that either provide, use or have experience in the application of noise abatement systems (NAS), such as bubble curtains or casings etc., during offshore wind farm (OWF) construction. We at SMRU Consulting are seeking technical information on the applicability and noise reduction efficacy of NAS and would be grateful if you would be willing to share your experience with us.

Scottish Natural Heritage have commissioned SMRU Consulting to provide a review of the current state of NAS. The aim of the review is to assess the applicability of NAS during OWF construction in Scottish waters. As part of this review we are contacting you as a NAS supplier, NAS user or OWF developer in order to fully understand the strengths and limitations of NAS with regard to the application of these under the conditions that prevail in future wind farm planning zones in Scottish waters. This questionnaire is a central element in a stakeholder consultation process that may go along with a telephone interview to clarify questions if you agree that we may contact you.

SMRU Consulting will evaluate the information you may provide: technical details of the NAS and which and to what degree environmental conditions found in Scottish waters will limit their applicability and efficacy. Parameters of interest are the benefit to marine fauna, practicality of use, cost, and impact on the OWF construction schedule. A secondary objective is the relative applicability of NAS to mitigate noise generated by underwater explosives (e.g. UXO).

SMRU Consulting will summarise the results of the stakeholder consultation, including the questionnaires' results, in a publically available final report published by SNH under the Freedom of Information Act 2000 (c.36). All personal data given in the contact details section will be treated as confidential under the general data protection regulation (GDPR). The completed questionnaires will not be forwarded to SNH and will be kept by SMRU Consulting as confidential material or deleted after the project if you wish so.

The questionnaire consists of six sections with a total of 38 questions on 6 pages, of which most of them you can answer by simply ticking boxes. Please take your time to fill in the questionnaire. It will take approximately 30 to 45 minutes to fill in the individual sections. We would like to pass on our sincere thanks to you for completing this questionnaire and send it back to us by **15th October 2018**. Please send the completed questionnaire and any further information you may wish to share to the Project Manager Dr. Ursula Verfuss (ukv@smruconsulting.com).

If you have any questions regarding the questionnaire or how the data you provide will be used, please do not hesitate to contact Ursula for more information.

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Instructions

The information that you kindly provide to us will be used to evaluate noise abatement systems (NAS). Contact information will be treated confidentially. The questions refer to the one NAS named in section 1 "NAS – basic information". If you wish to provide information on more than one NAS type or model, please fill in one questionnaire per NAS type or model. Please use the space at the end of the questionnaire or a separate sheet in case text boxes do not give you enough space to enter the relevant information. Thank you!

After the project, please let us know what to do with the questionnaire you completed

☐ Please delete the questionnaire

☐ Please keep the questionnaire for re-use in case the information can be used for future projects

☐ Please inform me in case that information will be re-used in another project.

Contact information

Name ______________________ Company ______________________

Phone number ______________________Email______________________

For further questions specific to this review ☐ I am happy to be contacted ☐ No, please do not contact me.

☐ Please contact the following person Name: ______________ Number or email: ______________

1 NAS - basic information

1) About yourself: You are a ☐ NAS supplier ☐ NAS user ☐ OWF developer

2) NAS system type:

☐ Big Bubble Curtain ☐ Casing ☐ Hammer (other than impact pile-driver)

☐ Resonator ☐ Other (please specify): ______________________

3) NAS system:

System name ______________________ Model ______________________

Manufacturer ______________________

Supplier (if different from manufacturer) ______________________

4) Current technology readiness level (TRL) of the NAS

☐ TRL 5: Large scale NAS prototype validated in nearshore or offshore environment.

☐ TRL 6: Full scale NAS prototype demonstrated in offshore environment.

☐ TRL 7: System prototype demonstration during offshore windfarm (OWF) construction.

☐ TRL 8: First of a kind commercial deployment during OWF construction. System certified and qualified.

☐ TRL 9: Full commercial application: System commercially deployed in more than one OWF project.

5) To which time frame does the information you provide in the NAS questions below refer to?

☐ Before 2012 ☐ 2012 to 2014 ☐ 2015 to 2017 ☐ After 2017

2 Scope of Application

6) Where is or was the NAS deployed?

☐ Directly on the pile (e.g. hammer other than impact pile-driver)

☐ In the vicinity of the pile (not more than up to 3 m away from pile)

☐ At a larger distance from the pile: Minimum distance________________ / Maximum distance______________

7) Can the NAS be used to reduce noise associated with UXO clearance / controlled underwater explosions?

☐ No / ☐ Yes

8) For which **piling operations** is the NAS suitable? (Please tick all that apply)

☐ In-air piling operations (hammer always above water surface)

☐ Underwater piling operations (hammer comes in contact with water)

9) For which **foundation types** is the NAS suitable? (Please tick all that apply)

☐ Monopiles

- If yes, is there a limitation on pile **diameter**? Max. pile diameter: ___________m / No limit ☐
- If yes, is there a limitation on pile **length**? Max. pile length: ___________ m / No limit ☐
- Other limitations? ☐ No / ☐ Yes please describe ____

☐ Piled jackets: pre-piling approach (pin piles installed using a piling template, jacket is then connected to the pre-installed pin piles)

- Are there any limitations regarding the **jacket footprint** or **pin pile diameter**?

  ☐ No / ☐ Yes - Please describe: ____

Other limitations? ☐ No / ☐ Yes - Please describe: ____

☐ Piled jackets: post-piling approach (jacket lowered to the seafloor and then fixed to the pre-installed pin piles)

- Are there any limitations regarding the **jacket footprint** or **pin pile diameter**?

  ☐ No / ☐ Yes - Please describe: ____

Other limitations? ☐ No / ☐ Yes - Please describe: ____

3 Logistical requirements

10) What is the average time needed to **mobilise** the NAS (from placing an order to arrival of the system at the quayside)?

____

11) What is the average time needed to **deploy** the NAS at a piling site? ________________________________

12) What is the average time needed to **recover** the NAS and prepare it for redeployment? ___________________

13) Which type of vessel(s) is / are needed to deploy, operate and recover the NAS? (Please tick all that apply)

	Deployment	*Operation*	*Recovery*
Auxiliary vessel	☐	☐	☐
Installation vessel	☐	☐	☐

14) What are the logistical requirements to deploy, operate and recover the NAS? (Please tick all that apply)

☐ Crane – required lifting capacity: ____________ tons / Lifting height: ____________ m

☐ Deck space requirement for NAS + auxiliary equipment (e.g. power pack, compressors, etc.): ____________ m^2

Is a modification of pile gripper needed? ☐ No / ☐ Yes / ☐ Not Applicable

Can the NAS be automatically released/retrieved from the pile gripper? ☐ No / ☐ Yes / ☐ Not Applicable

☐ Other (please specify): ____

15) Can the NAS and auxiliary equipment be stored in standard containers?

System: ☐ No / ☐ Yes   Auxiliary equipment: ☐ No / ☐ Yes

16) What is the overall weight of the NAS (incl. accessories, but without auxiliary equipment)? ________kg

17) What consumables are needed to operate the NAS and in what quantities (per piling operation)?

☐ Fuel/diesel: ________ litre   ☐ Gas: ________ m^3 ☐ Other (please specify): ________________

18) Which processes will or may incur additional time for the piling process of a foundation with usage of a NAS compared to without a NAS? (Please tick all that apply, and indicate the minimum and maximum time)

☐ NAS preparation (on site): minimum _______ minutes   maximum _______ minutes

☐ NAS deployment: minimum _______ minutes   maximum _______ minutes

☐ NAS operation: minimum _______ minutes   maximum _______ minutes

☐ NAS recovery: minimum _______ minutes   maximum _______ minutes

☐ None   Any further comments on this matter? ____

19) Who will deploy and operate the NAS?

☐ EPC / EPCI contractor   ☐ OWF developer   ☐ NAS supplier

☐ How many staff are needed to deploy and operate the system (minimum)? ____________________________

20) Based on your experience, during an OWF project with 80 foundations, how many NAS malfunctions can be expected (expressed as number of foundations piled without or with limited noise mitigation)?

☐ None   ☐ 1-3   ☐ 4-7   ☐ >= 8

21) What mitigation measures are in place for the event that the NAS malfunctions?

____

22) How long does it typically take (approximately) to repair a typical NAS malfunction or to provide a replacement system?

Repair ________ ☐ Hours / ☐ Days / ☐ Weeks   Replacement _______ ☐ Hours / ☐ Days / ☐ Weeks

Other (please specify): ____

23) Are there any special HSE requirements to be considered, e.g. with regard to hazardous materials or consumables?

☐ No / ☐ Yes - Please specify: ____

4 Deployment and operational limitations

24) What is the water depth the NAS was / can be deployed and successfully operated in? (Please tick all that apply)

	In theory	*Field proven*	*Commercially deployed*
0 to 10 m:	☐	☐	☐
10 to 20 m:	☐	☐	☐
20 to 30 m:	☐	☐	☐
30 to 40 m:	☐	☐	☐
40 to 50 m:	☐	☐	☐
50 to 60 m:	☐	☐	☐
60 to 70 m:	☐	☐	☐
>70 m:	☐	☐	☐

Maximum operational depth: ____________ m

25) What are the limiting geological conditions for the deployment / operation of the NAS? (Please tick all that apply).

☐ No limiting geological conditions

	Deployment	*Operation*
☐ Soft substrate surface layer	☐	☐
☐ Medium dense substrate	☐	☐
☐ Hard substrate	☐	☐

Limiting because (Soft substrate surface layer) ____

Limiting because (Medium dense substrate) ____

Limiting because (Hard substrate) ____

26) Are there restrictions regarding the **<u>range</u> of water depths** (variation in depth) **across a given construction site** for applying the NAS?

☐ No ☐ Yes, application is restricted when depth range is varying more than ____________ m.

27) What are the limiting metocean conditions for the deployment / operation of the NAS? (Please tick all that apply)

	Deployment	*Operation*	*Limiting because*
☐ Max wind speed (at 10 m height)	_______ m/s	_______ m/s	______________________
☐ Max significant wave height (Hs)	_______ m Hs	_______ m Hs	______________________
☐ Max speed of local currents	_______ m/s	_______ m/s	______________________
☐ Min visibility	_______ m	_______ m	______________________
☐ Min temperature	_______ °C	_______ °C	______________________

☐ Other (please specify): ____

5 Cost implications

Please help us to understand the cost implications.

28) What is the main costs driver that determines the overall costs for the NAS usage?

☐ Modification of equipment (e.g., pile gripper) ☐ Extra offshore time ☐ System rental costs

☐ Vessel costs ☐ Other, Please specify ____

29) Please indicate the percentage increase of the substructure installation costs (foundation installation and scour protection, excluding foundation CAPEX) for the application of the NAS (at wind farm level), compared to installation without a NAS: Installation cost increase is around __________% or __________€

30) What are the approximate rental costs of the NAS (in million €) when offered for the application at an OWF project in UK waters for a project installing 80 foundations within 12 months' time (not including optional items)?

☐ Up to €5m ☐ €5m to €10m ☐ €10m to €15m ☐ More than €15m ☐ Not known ☐ Confidential

31) What do the NAS rental costs include (please tick all that apply)?

☐ Personnel deploying and operating the NAS ☐ Auxiliary vessel incl. fuel ☐ Consumables

☐ Auxiliary equipment needed to operate the NAS ☐ Energy supply ☐ Not sure

32) If rental costs do not include the above, which of them could be included as an option and how much would it increase the rental cost? (Please tick all that apply)

☐ Personnel deploy/operate the NAS Increases costs by approximately _______% or _______€

☐ Auxiliary vessel Increases costs by approximately _______% or _______€

☐ Auxiliary equipment to operate the NAS Increases costs by approximately _______% or _______€

☐ Energy supply Increases costs by approximately _______% or _______€

☐ Consumables Increases costs by approximately _______% or _______€

6 Noise reduction efficacy

33) Can you control the frequency range within which the noise will be reduced? ☐ No / ☐ Yes

If yes, how it will be controlled: ____

How does it affect the frequency spectrum? ____

34) How much do the following environmental factors influence the noise reduction efficiency on a scale from 0 (no influence) to 6 (strong influence)? Please specify the influence:

- Water depth: Scale_______ Details ____
- Soil geology: Scale_______ Details ____
- Current speed: Scale_______ Details ____
- Other: ________ Scale_______ Details ____

35) Which technical factors affect the noise reduction efficiency and how? (e.g., for bubble curtain: air volume, hose length, nozzle size etc.). Please list factors and a short explanation on how they affect the noise reduction efficiency.

36) How was the noise reduction efficiency investigated?

☐ Modelled ☐ Field measurements

37) If field measurements were conducted, did they follow any standards?

☐ No ☐ I don't know ☐ Yes – please specify:

☐ DIN SPEC 45653:2017 Offshore wind farms - In-situ determination of the insertion loss of control measures underwater

☐ ISO 18406:2017 (en) Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving

☐ BSH Measuring instructions

☐ NPL Good Practice Guide for Underwater Noise Measurement

☐ Other standard (please specify):

____

38) Would you be willing to share reports of studies on the NAS noise reduction efficacy for further analysis? They will be used to answer the questions on the next page.

☐ Yes ☐ Yes, but please keep the name of the OWF confidential

☐ Yes, but only under NDA and with the restriction to review the outcome of the analysis

☐ No ☐ No, but I am happy to answer the set of questions on the noise reduction efficacy given on the next page)

If yes, please send the reports to us along with the completed questionnaire to ukv@smruconsulting.com

Please let us know if you have any further comments:

7 Questionnaire on noise reduction efficiency

If you are providing SMRU Consulting with reports on the NAS noise reduction efficacy you **do not** need to fill in this section. However, if you cannot share reports but are happy to answer a separate set of questions on the noise reduction efficacy of the NAS(s), please could we kindly ask that you complete this additional section. Please note below if a single or a combination of systems for the reduction of noise was investigated.

Name of the OWF: ______________________________ ☐ Please tick if OWF name should be kept confidential

Water depth of OWF (m): ____________ Year of investigation: ____________

Number of NAS systems used simultaneously in the study: ______________________________

NAS system(s) / model(s) used in the study: ______________________________

Technical set-up of the NAS(s): ______________________________

Technical set-up of the noise monitoring equipment: ______________________________

What is the noise reduction efficiency the NAS provided (***in dB relative to unmitigated situation***) for the following **unweighted** noise parameters? Please state the distance to the pile which the reduction refers to:

____

- Zero-to-peak sound pressure level $L_{0\text{-}pk}$:

  Measured: minimum _______ dB typical _______ dB maximum _______ dB

  Modelled: minimum _______ dB typical _______ dB maximum _______ dB

- Broadband noise single strike sound exposure level (SEL):

  Measured: minimum _______ dB typical _______ dB maximum _______ dB

  Modelled: minimum _______ dB typical _______ dB maximum _______ dB

- Frequency dependent reduction of SEL averaged over the frequency range

  - **at 250 Hz**

  Measured: minimum _______ dB typical _______ dB maximum _______ dB

  Modelled: minimum _______ dB typical _______ dB maximum _______ dB

  - **at 1 kHz**

  Measured: minimum _______ dB typical _______ dB maximum _______ dB

  Modelled: minimum _______ dB typical _______ dB maximum _______ dB

- Frequency dependent reduction of SEL averaged over the frequency range

  - **at 100 Hz**

  Measured: minimum _______ dB typical _______ dB maximum _______ dB

  Modelled: minimum _______ dB typical _______ dB maximum _______ dB

  - **at 500 Hz**

  Measured: minimum _______ dB typical _______ dB maximum _______ dB

  Modelled: minimum _______ dB typical _______ dB maximum _______ dB

If you have any reports or references you are referring to or which would be helpful for us to evaluate the noise mitigation efficacy please cite them here:

If you have any further information on the noise reduction efficiency the system you would like to share with us please let us know here:

Thank you very much for your efforts!

Dr Ursula Verfuss

Principal Scientist

SMRU Consulting

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