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BEST AVAILABLE TECHNOLOGY (BAT) AND BEST ENVIRONMENTAL PRACTICE (BET) FOR THREE NOISE SOURCES: SHIPPING, SEISMIC AIRGUN SURVEYS, AND PILE DRIVING

(Prepared by OceanCare)

Summary:

This work provides inputs relevant to the work of the Scientific Council under Decision 12.43 to *assess the need for, and if required develop, voluntary guidelines on activities of concern*, and would contribute to meeting the recommendation in Resolution 12.14 that *Parties, the private sector and other stakeholders apply Best Available Techniques (BAT) and Best Environmental Practice (BEP) including, where appropriate, clean technology, in their efforts to reduce or mitigate marine noise pollution*.

UNEP/CMS/COP13/Doc.26.2.2 recommends that the CMS/ACCOBAMS/ASCOBANS Joint Noise Working Group is requested to review this report and that the Secretariat publishes the resulting version as a Technical Series to make the information easily accessible to Parties.

Best Available Technology (BAT) and Best Environmental Practise (BET)
for Three Noise Sources:
Shipping, Seismic Airgun Surveys, and Pile Driving

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Abstract

The application of Best Available Techniques/Technology (BAT) and Best Environmental Practice (BEP) is required under several international agreements and conventions. For shipping noise, this generally includes minimizing cavitation, better maintenance, and optimizing the propeller design to the hull and to usual operating conditions, which often improves efficiency as well. Focusing quieting on the 10-15% of the noisiest container and cargo ships will go furthest in reducing overall shipping noise. Slow steaming, or reducing ship speed mainly to save fuel, from an average of 16 kts to 14 kts (12% speed reduction) as was done in the Mediterranean, probably reduced the overall broadband acoustic footprint by over 50%. Slow steaming has the advantage that no retrofitting is required and greenhouse gas emissions are reduced. For seismic airgun surveys, quieting technologies, such as Marine Vibroseis, that could replace airguns show the most promise, as much of the energy (the mid- or high-frequencies) emitted by airguns is wasted and unused. A controlled sound source, like Marine Vibroseis, tailor-made to the specific environmental conditions and without the damaging short rise time of airguns would also likely be more environmentally friendly towards marine life. Mitigation measures for airgun surveys should show proof of their efficacy and should include: avoiding sensitive areas and times, not proceeding in conditions of poor visibility such as at night, establishing statistically meaningful baseline studies of biological abundance and distribution, and provide a thorough quantitative analysis of synergistic and cumulative impacts from other noise and non-noise stressors. Many new quieting technologies and alternative low-noise foundation concepts have been developed for pile driving, mainly due to the German government setting an action-forcing standard and noise limit. The great variety of quieting technologies and noise abatement systems for pile driving is in stark contrast to the lack of innovation that is occurring for quieter alternatives to the seismic airgun. Best Environmental Practice is somewhat similar to that for seismic airgun surveys. Even though at least 130 marine species have shown impacts from ocean noise pollution, managing this threat is best done using a precautionary approach (i.e. quieting), due to the difficulty in detecting the exact scenario where ecosystem and population consequences from underwater noise occur. Especially where quieting also reduces greenhouse gas emissions and encourages technological innovation, this approach is likely the most effective.

To prevent and reduce marine pollution, the application of Best Available Techniques/Technologies (BAT) and Best Environmental Practice (BEP) is a requirement recognized and promoted within Decisions and Resolutions adopted by the Parties under several international agreements and conventions, e.g. under the Convention on Migratory Species (CMS) and the Convention on Biological Diversity (CBD). Regional Agreements, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and of the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention), as well as species-focused regional agreements, including the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS), also require BAT and BEP.

BAT for Shipping Noise

Noise levels

Peak spectral levels for individual commercial ships are in the frequency band of 10 to 50 Hz and are around 195 dB re µPa^2/Hz at 1 m for fast-moving (>20 knots) supertankers (Hildebrand 2009). A cargo vessel (173 m length, 16 knots) had a source level of 192 dB over a 40–100 Hz bandwidth (Hildebrand 2009). This does not mean that shipping noise is restricted to these low frequencies, however. Especially close by and in shallow water, shipping noise can extend into the high kilohertz (kHz) range. Hermannsen et al. (2014) found that vessel noise from various different ship types considerably raised noise levels across the entire recording band from 25 Hz to 160 kHz at ranges between 60 and 1000 m. The authors estimated that these noise levels caused a hearing range reduction in animals such as the harbour porpoise of more than 20 dB (at 1 and 10 kHz) from ships passing at distances of 1190 m, and more than a 30 dB reduction (at 125 kHz) from ships at 490 m distance or less (Hermannsen et al. 2014). This hearing range reduction (20-30 dB) represents a 100- to 1000-fold reduction in intensity.

Impacts

Shipping noise is associated with increased stress levels in endangered North Atlantic right whales (Rolland et al. 2012). Pirotta et al. (2012) found that broadband ship noise caused a significant change, over a distance of at least 5.2 km, in beaked whale movement while they were foraging, which could reduce their food intake. Routine vessel passages reduced communication space by up to 61.5% for bigeye fish and 87.4% for Bryde's whales, and by up to 99% for both species during the closest point of approach of a large commercial vessel (Putland et al. 2018). Larval Atlantic cod exposed to shipping noise in the laboratory were in worse condition and easier to catch in a predator-avoidance experiment (Nedelec et al. 2015). Indicators of stress increased with ship noise playbacks in European perch, common carp, and gudgeon (Wysocki et al. 2006), European sea bass and gilthead sea bream (Buscaino et al. 2010; Celi et al. 2016), juvenile European eels (Simpson et al. 2015), as well as shore crabs (Wale et al. 2013). Shipping noise caused bluefin tuna schools to become uncoordinated, which could affect their homing accuracy during migration (Sarà et al. 2007).

Excessive underwater noise from ships is mainly caused by poor propeller design or one not correctly matched to the vessel and its usual operating conditions; poor ship hull design especially of the aft end of the ship, causing an uneven water flow into the propeller (poor wake field); or a fouled (dirty) or damaged propeller. A particularly noisy propeller means the ship is probably operating inefficiently. Solutions to existing ships include installing new, more efficient propellers, good maintenance of propellers (cleaning and repairing damaged ones), using devices to improve the wake flow into the propeller, and maintaining the hull well.

Propeller cavitation

Propeller cavitation is a major source of shipping noise. It is caused by the formation and collapse of air bubbles on the surface of a rotating propeller when the pressure falls below the vapor pressure of water, causing a hissing noise. It is broadband, across a wide range of frequencies, but with narrow-band or tonal peaks of noise occurring together with the rotation rate (rpm) multiplied by the number of blades of the propeller, and the harmonics thereof. The lowest speed where cavitation starts to occur is known as the cavitation inception speed (CIS). For many ships, the CIS is around 10 kts or even lower (Leaper and Renilson 2012). Some cavitation occurs even with efficient propellers, but excessive cavitation from the noisiest ships is a sign they may be operating inefficiently, with poor wake flow into the propeller and/or poor propeller design (Leaper et al. 2014). If noise from one source of noise is 10 dB above other sources of noise, then those other sources are mostly irrelevant (McCauley et al. 1996). For the noisiest merchant ships, the propeller cavitation noise is likely to dominate other noise sources from that ship (IMO 2013). Cavitating propeller noise dominates other propeller noise, other than singing (high-pitched notes), and all other hydro-acoustic noise from a ship (Ligtelijn 2007). Propeller singing is easy to fix by changing the shape of the trailing edge (Leaper and Renilson 2012).

Focus on the noisiest vessels
There have been differences of 20-40 dB reported between the quietest and noisiest ships of a similar type (Carlton and Dabbs 2009), showing large differences in levels at certain frequencies. Leaper and Renilson (2012) estimated that the noisiest 10% of vessels (those that are 6.8 dB or more over the average) contribute to 48-88% of the total acoustic footprint (the sea area over which the ship noise increases the background noise over a certain level). Veirs et al. (2018) found that, of 1,582 ships measured in the Haro Strait between Seattle and Vancouver, half of the total power radiated by this modern fleet came from just 15% of the ships--those with source levels above 179 dB re 1 μPa at 1 m. More than two-thirds of these worst noise polluters were cargo and container ships (Veirs et al. 2018). About 43% of container ships were worst polluters, by far the highest proportion of any ship class of those studied (Veirs et al. 2018).

Overlap between increased energy efficiency and noise reduction
As Leaper and Renilson (2012) explain it, a greater blade area can produce the same thrust but with a smaller difference in pressure between the face (pressure side) and the back (suction side) of the blade. Since the difference in pressure causes cavitation, cavitation will be reduced with increased blade area. However, this greater blade area also increases the necessary torque required to turn the propeller. For merchant ships, there is an optimum design in terms of efficiency that is a trade off between cavitation and blade area. In most cases, an optimally efficient propeller involves a certain amount of cavitation in order to minimize blade area. It should be the goal, however, to reduce *excessive* cavitation which can reduce the thrust and also cause erosion on the propeller and even on the rudder, in some cases (Leaper and Renilson 2012).

Many propellers are probably not currently designed for optimum efficiency. As their design improves for efficiency, there are stages where more efficient propellers are also quieter. As explained above, propellers designed for maximal quieting may not be the most efficient, however, as once optimal efficiency is attained, there is a trade-off between efficiency and noise quieting. Most propellers in existence now are likely neither optimally efficient nor optimally quiet, though, so there is room for improvement on both fronts where the same modifications can work towards both goals. In situations where excessive cavitation is associated with poor efficiency, the solution would also lower noise.

The other major factor involved in reducing propeller cavitation is improving the wake flow around the hull ahead of the propeller. Ideally, the wake should be as uniform as possible, so that the propeller, as it rotates through its full circle, does not experience much of a difference in flow. A non-uniform wake can reduce propulsive efficiency and cause the cavitation to fluctuate through the rotation cycle, producing tonal noise and harmonics thereof.

Propellers should be clean, free of fouling, polished, and well-maintained, with no nicks or imperfections, especially on the leading edge (Leaper and Renilson 2012). Such damage can cause more cavitation, reduce efficiency by 2%, and cause noise (Leaper and Renilson 2012). Well-built and well-designed propellers can help with efficiency and noise, and care should be taken to design the propeller and hull as a unit, so that the wake field is taken into account. Designs of propellers and hulls should suit the actual operating conditions, not the ideal. This would also improve propulsive efficiency and reduce noise (Leaper and Renilson 2012).

Propellers can also generate vortices from their hub which reduce efficiency and are prone to cavitate (Leaper and Renilson 2012). They also tend to cause higher frequency noise. Efficiency gains and noise reduction can be achieved by well-designed hub caps as well devices that can be affixed to the hub such as Boss Cap Fins and Propeller Cap Turbines (Leaper and Renilson 2012).

Wake inflow devices can improve the wake going into the propeller, reducing cavitation and likely increasing efficiency while reducing noise. Devices that can be fitted to the hull for this purpose include the Schneeekluth duct, Mewis duct, and Grothues spoilers (Leaper and Renilson 2012).

In 2009, the IMO (International Maritime Organization) recommended that member states should identify the vessels in their merchant fleets that would benefit most from efficiency-improving technologies as these would also likely make their ships quieter (IMO 2009a). Most importantly, as fuel efficiency and greenhouse gas emissions are tackled, it would be a missed opportunity to not address noise at the same time, as there is certainly some overlap. Small changes in propulsive efficiency can dramatically lower noise output (Leaper and Renilson 2012).

Hull vibration, engine and machinery noise
Vibration isolation, noise insulation, and damping are the main treatments to reduce noise and vibration to the hull. The most challenging to quiet are large, slow-speed diesels, variable speed equipment, very light equipment, and emergency generators.

Onboard real-time noise monitoring
A real-time noise monitoring system for both engine and propeller noise would also be helpful to have onboard, so that ship operators can get immediate feedback about which operating conditions are producing the most noise. For propeller noise, an accelerometer can be mounted near the propeller for real-time noise monitoring onboard. This can tell the operator which conditions alter the cavitation inception speed.

Technological quieting measures
A report was prepared for Transport Canada by Vard Marine Inc. (Kendrick and Terweij 2019) to systematically go through all the technological quieting measures for ship underwater radiated noise. This did not include operational or maintenance measures. A table was included in the report which is copied in the Appendix, with permission. The matrix was developed by Vard Marine on behalf of Transport Canada, and is based on an extensive literature search and the input of industry experts in a series of workshops (Kendrick and Terweij 2019).

BEP for Shipping Noise

Slow steaming to reduce noise and greenhouse gas emissions
Slow steaming is the practice of operating transoceanic cargo ships, especially container ships, at substantially slower speeds than their maximum, mainly to save fuel. Slow steaming has the advantage that no retrofitting is required so can be implemented immediately. For ships with a fixed pitch propeller, which are the majority, reducing the speed reduces the overall noise, though levels may not necessarily decrease across all frequency bands (Leaper and Renilson 2012). Leaper et al. (2014) noted

that slow steaming practises since 2007 reduced average speeds from 15.6 kts (sd = 4.2) in 2007 to 13.8 kts (sd = 3.0) in 2013 for ships using the major shipping routes in the eastern Mediterranean. This 11.5% reduction in average speed probably reduced the overall broadband acoustic footprint from these ships by over 50% (Leaper et al. 2014). For ships around the Haro Strait (between Seattle and Vancouver), 3 dB of overall noise reduction (i.e. a 50% reduction in sound energy) could be met by enforcing a speed limit of 11.8 knots (Veirs et al. 2018). The average ship speed across all classes was 14 kts; the average for container ships alone was 19 kts. This speed limit would affect 83% of the ships studied (Veirs et al. 2018).

Slow steaming across shipping fleets has also been shown to be an effective short-term measure to reduce greenhouse gas emissions. In April 2018, the IMO adopted the goal to reduce the total annual greenhouse gas emissions by at least 50% by 2050 compared to 2008. Leaper (submitted) reviewed modelling work on greenhouse gas emissions, and how that related to underwater noise, ship-whale collision risk, and ship speed. He took into account research which considered that slow steaming would increase the number of vessels needed to transport the same volume of goods, the cost of operating those extra vessels, and the increase in ship construction that might be necessary. Faber et al. (2017) examined speed reductions of 10, 20 and 30% compared to 'business as usual'. They found that in 2017, 3.5% of container vessels were idle or laid up and estimated that bringing these vessels back into service would allow the container fleet to reduce speeds by 8% (Faber et al. 2017). Speed reductions of greater than 10% would probably require an increase in fleet capacity to meet current demand (Leaper, submitted). According to an economic model developed by Lee et al. (2015), the savings in total fuel consumption from slowing down was usually higher than the cost of operating the extra vessels necessary to transport equivalent goods. In addition, slow steaming also had business advantages beyond saving fuel in that it increased delivery time reliability (Lee et al. 2015). Leaper (submitted) examined various speed reduction scenarios which would help achieve the greenhouse gas reduction targets, while at the same time offering additional environmental benefits of reducing noise and the risk of ship strikes on whales. Leaper (submitted) concluded that modest, 10%, reductions in speeds across the global fleet could reduce the total sound energy produced by shipping by around 40%.

The reduced risk of ships striking whales was harder to estimate, with greater attendant uncertainty, but could be around 50% (Leaper, submitted). When slow steaming is used, the propellers and hull should be redesigned for this operational difference, especially controllable pitch propellers (Leaper and Renilson 2012). The proportion of the long-distance commercial fleet with controllable pitch propellers is very low, but consideration of noise from such propellers may be important in localized situations, for example where CPPs are fitted to ferries.

While slower speeds with the same fixed pitch propeller will almost certainly substantially reduce noise levels because cavitation will be reduced, it is more complicated if the propeller is optimised for the slower speeds in terms of fuel efficiency. This is because optimising for fuel efficiency may involve reduced blade area and accepting a greater amount of cavitation. There is a need to consider underwater noise as well as fuel efficiency when making such modifications such that noise is not inadvertently increased by optimising for fuel efficiency.

Vessel load condition

Propellers are usually designed for vessels carrying a full load, despite ships not spending all their time in this state (Leaper and Renilson 2012). In ballast, the ship is never loaded close to its full load condition, which means the propeller is closer to the surface. The propeller tip may even be above the waterline. In ballast, the degree of cavitation on a propeller can be increased because of the reduction in water pressure on the blades, despite reduced propeller loading (Paik et al. 2013). On top of that effect, a ship in ballast is usually trimmed by the stern which worsens the wake field to the propeller, causing yet more cavitation (Leaper and Renilson 2012). Altogether, this means a tanker or bulk carrier in ballast will often be noisier than one in full load (Leaper and Renilson 2012).

Cold ironing

Cold ironing is the practise of using a shoreside electrical power connection when a ship is at berth in port while its main and auxiliary engines are turned off. It is also called shore-to-ship power (SSP) or alternative maritime power (AMP). There is obviously less underwater noise with cold ironing, as well as fewer emissions. There may be an added advantage of cold ironing in that it may reduce biofouling on ship hulls. Several studies have shown faster settlement of mussel larvae or other biofouling organisms with ship or generator noise (Wilkens et al. 2012; McDonald et al. 2014; Stanley et al. 2014; Jolivet et al. 2016). Only one study showed a low-frequency sound inhibiting only very young barnacle larvae from settling (Branscomb and Rittschof 1984). Reducing biofouling can save money (the U.S. Navy spends US$1 billion every year and US$56 million per single Navy vessel class on biofouling—McDonald et al. 2014), reduce noise (biofouling increases turbulence), increase efficiency, and even avoid the spread of invasive species on hulls. Vessel hull biofouling can be responsible for at least 75% of the invasive species brought in by ships (McDonald et al. 2014). A clean vessel entering a port infected with invasive species and running a generator could attract pest species from about a 500 m radius (McDonald et al. 2014).

Maintenance

Keeping the hull and propeller clean and repaired can yield cost savings, efficiency gains, and noise reductions. Other onboard machinery and engines will almost certainly be quieter and more efficient when well-maintained.

Shipping lane re-routing around important habitat

Re-routing shipping lanes around areas rich in marine life can reduce ship-whale collision risk as well as reduce exposing sensitive areas to noise. Routing measures already exist within PSSAs (Particularly Sensitive Sea Areas) designated by the IMO. Noise should be added as another criteria in choosing or expanding the size of PSSAs. Sensitive areas need additional noise buffers as noise can travel long distances.

Avoiding times/areas of high sound propagation

Sound propagates or travels further in certain conditions. Noise produced at the surface can enter the deep sound channel, in which sound travels long distances very efficiently, where the sound channel intersects with features such as the continental slope (Leaper and Renilson 2012). The sound channel is very close to the surface in high latitudes. In colder months, sound is also transmitted further. Thus, to reduce the spread of shipping noise, ships should avoid or reduce the amount of time travelling parallel to the continental slope or shelf by staying further offshore and if they must cross the continental shelf, do so at right angles, avoid or reduce time at colder, higher latitude waters, and operate in the warmer months where possible.

Port incentives

The Port of Vancouver and the Port of Prince Rupert both give incentives to quieter ships in that they offer reductions in docking fees and harbor dues of up to almost 50%. Such incentives should be expanded to other ports worldwide to create a level playing field.

Certification programs
Green certification programs that incentivize quieter ships such as Green Marine can help reduce ocean noise pollution from shipping. Ships that reduce emissions and are otherwise more environmentally friendly can gain standing and ranking, and are able to advertise their green credentials.

Underwater noise management plans
Underwater noise management plans should be developed for entire fleets. Transport Canada has encouraged Canadian fleet operators to have plans to reduce their fleet's overall noise output.

Noise consideration in ship design
If tank testing facilities and model basins measured noise routinely and incorporated noise reduction as a factor in good ship design, ships would be designed to be quieter from the onset. With the emphasis on ever increasing fuel efficiency, there are opportunities to improve the design process of ships such that the design starts with the propulsion system rather than designing a propulsion system to suit a given hull design. This has the potential to improve efficiency and reduce underwater noise.

BAT for Seismic Airgun Survey Noise

Noise levels
An airgun array has a source level of around 260 dB re 1 µPa at 1 m, with a bandwidth of 5-300 Hz (Hildebrand 2009). While the energy from airgun impulses is mostly concentrated in the lower frequencies, there is still substantial energy in the tens of kHz to even over one hundred kHz (Goold and Coates 2006).

Impacts
Fin whales were displaced from their habitat when a seismic survey started, and the displacement lasted well beyond the length of the seismic survey (Castellote et al. 2012). Bowhead whale calling was repressed within a 50–100 km radius of a seismic survey, which represents 8,000-30,000 sq km in area. Within 10–40 km of the seismic survey, or 300–5,000 sq km, bowhead calling was almost entirely absent (Blackwell et al. 2015). Pirotta et al. (2014) found that the probability of recording a prey capture attempt by harbour porpoise declined by 15% in the area exposed to seismic survey noise and increased the further away the seismic vessel was. Seismic airgun noise killed zooplankton, especially immatures, with a 2-3 fold-increase in dead zooplankton (McCauley et al. 2017). Day et al. (2017) identified a 5-fold increase in mortality in scallops subjected to four passes of an airgun. These effects occurred 4 months after exposure to the airgun ceased. Fitzgibbon et al. (2017) discovered that southern rock lobsters showed a chronic reduction of immune competency and impairment of nutritional condition, also 120 days post-airgun exposure. Moreover, lobsters showed significant damage to sensory organs, impairing important reflexes, even a year post-exposure to an airgun (Day et al. 2019). Catch rates for haddock, cod, and rockfish dropped from 21-70% (Engås et al. 1996; Skalski et al. 2004) during or after seismic airgun surveys. Declines in fish abundance also were documented (Slotte et al. 2004; Paxton et al. 2017).

Leaper et al. (2015) found that there are seldom cases where mitigation based on visual observation can achieve a greater risk reduction than would be achieved by a 3 dB reduction in source level throughout the survey. This is because Marine Mammal Observers (MMOs) cannot spot many marine mammals and turtles since they are cryptic, elusive, often underwater, and since survey activities often take place at night and in other limited-visibility conditions. The use of MMOs therefore only results in a limited risk reduction in all cases (Leaper et al. 2015). Consequently, probably the most effective mitigation for seismic airgun surveys is to: a) separate the surveys from areas rich in marine life and sensitive species; and b) to lower the source level (quiet the noise).

As mentioned, there is still considerable energy in the tens of kHz from airguns, extending even to over 100 kHz (Goold and Coates 2006), which explains why cetaceans (whales and dolphins) with middle or higher frequency sensitivities react to the noise (Goold and Fish 1998). Geophysicists and the oil and gas industry do not make use of, nor even record, any energy over about 200 Hz, however. This wasted energy therefore needlessly impacts marine life, especially animals with mid- or high-frequency hearing. There is currently considerable effort being expended by a number of companies to develop alternative marine seismic sources that are expected to have a reduced environmental impact while being at least as effective as airgun arrays as sources for marine seismic exploration. The basic principle is to replace the short, high amplitude, wide frequency-bandwidth signal produced by an airgun array with a much longer, lower-amplitude signal, with the same acoustic energy in the frequency band required for the seismic survey (below 200 Hz and sometimes below 120 Hz), but with as little energy as possible outside that band. In a nutshell, the useful signal would have the same energy, just spread over a longer duration, allowing for a lower source level and less wasted energy at frequencies that are not used. The effectiveness of a signal for seismic surveying is determined solely by the signal's energy and bandwidth, so a longer, quieter signal should be just as effective as a shorter, louder one provided they have the same energy and cover the necessary frequencies (<200 Hz). The quieter signal should reduce the risk of damage to an animal's hearing at short range, and the narrower bandwidth should reduce the risk of negative impacts to species with mid- and high-frequency hearing.

Marine Vibroseis (MV)

Much of the industry effort is focused on developing a marine vibrator or marine Vibroseis (MV) system that can produce a controlled amplitude signal with a frequency that varies with time. MV is an example of a so-called "controlled source" since, unlike the air bubble produced under high pressure by an airgun shot, the sound it produces can be modified (frequency, duration, amplitude, etc.) in real time. A controlled source has specific spectral properties which allows for the necessary seismic information to be extracted using lower levels of energy, for instance through improved signal processing (LGL and MAI 2011), which would reduce the environmental impact. This method has been used successfully in land-based seismic exploration for many years. In 2009, when the Okeanos Foundation held a workshop entitled "Alternative Technologies to Seismic Airgun Surveys for Oil and Gas Exploration and their Potential for Reducing Impacts on Marine Mammals", the 16 participants also came to the conclusion that controlled sources such as marine vibrators probably offer the best chance at eventually replacing airguns (Weilgart 2010).

Tenghamn (2006) introduced a completely new electro-mechanical MV concept, using frequencies from 6 to 100 Hz. Pramik (2013) reported that, as MV is a scalable source, output level can be adjusted to environmental and operational conditions much more readily than with airgun arrays. MV output can be changed by altering the number of vibrators used in the array (more difficult with airguns due to undesirable acoustic side effects), by changing the output drive level, and by changing the length of the sweep (Pramik 2013). The controllable nature of the MV source could also bring advantages in signal processing.

Most airgun arrays have an effective source level of 255 dB (0-p) in the downward direction, compared with a MV array of about 223 dB rms (Bird 2003). Since the decibel scale is logarithmic, this is more than a 1,000-fold difference in intensity. LGL and MAI (2011) estimated that a MV survey would expose only about 1–20% of whales and dolphins to high noise levels when compared to those exposed to an airgun survey, based on their models. High peak pressure and rapid rise time or onset (sounds quickly increasing in amplitude), both of which describe airgun emissions, are two characteristics of sound thought to be particularly injurious to living tissues (Southall et al. 2007). Southall et al. (2007) believe a non-impulsive sound such as MV would have to be 12–17 dB louder than an airgun-like impulse to cause the same degree of injury, due to the damage inflicted by the rapid rise time. Additionally, Duncan et al. (2017) modelled sound levels from a realistic MV array and airgun array with similar downward energy at frequencies < 100 Hz and compared the two under various scenarios. They found that at a 100 m range, MV was 20 dB lower in peak-to-peak sound pressure level vs. the airgun array, decreasing to 12 dB lower at a distance of 5 km, the maximum modelled range for peak levels. MV also produced 8 dB lower Sound Exposure Levels (SELs), a metric which incorporates the duration of exposure, than the airgun array at 100 km range because of MV's reduced bandwidth (Duncan et al. 2017). Thus, there are benefits to MV even at long ranges and even for animals with good low-frequency hearing. Duncan et al. (2017) also found that changing the layout of the MV array's higher frequency sources reduced sound exposure levels (SELs) by 4 dB.

MV can also be used over a broader range of depths than airguns can, in deep water, shallow water, and transition zones. Therefore, the implementation of MV will most likely start in shallow water and transition zones, where it can be operationally superior to airguns (CSA Ocean Sciences Inc., 2014). Shallow water is also where MV's lower SEL advantage is most obvious, as SELs drop off more rapidly in these waters. In addition, shallow waters are often the most productive and biologically rich.

In summary, Duncan et al (2017) listed the main benefits of MV over airguns as:

- Lowering peak pressure (sound level) over short ranges
- Eliminating rapid rise time
- Eliminating unnecessary middle and high frequencies
- Lowering Sound Exposure Levels for distances of over 10 km
- Allowing for greater control and tailoring of the signal (amplitude, frequency, duration, etc.) in real time
- Operationally superior in shallow water and transition zones

MV thus shows potential in providing an environmentally safer alternative to airguns without compromising effectiveness for seismic exploration. LGL and MAI (2011) state that MV surveys would be expected to cause less of an impact (behavioral, physiological, auditory) than airgun surveys in all habitats and environments regardless of water depth or environmental conditions. The acoustic footprint, as measured in terms of peak-to-peak pressure, is substantially smaller for the MV array than the airgun array. The approximately 20 dB reduction in short-range peak-to-peak pressure levels decreases the safety or exclusion zone radius by roughly a factor of ten, translating to a reduction in safety zone area of about a factor of one hundred, which could greatly reduce the number of animals exposed to sound likely to cause injury.

The greatest drawback of MV compared with airguns is the greater potential for masking, since the MV signal is of longer duration (seconds vs. tens of milliseconds for an airgun pulse), and MV will likely have a higher duty cycle (percentage of time it is "on"). Some estimates of MV signal duration range from 5-12 s (LGL and MAI 2011). This would impact mainly low-frequency hearing specialists such as baleen whales and some fish. Slight masking effects could extend to a few tens of kilometers from the MV source. Using narrow-band FM sweeps as the MV signal would likely ameliorate the potential for masking (LGL and MAI 2011). Moreover, airgun pulses are also not always as short in duration as they appear, if heard over larger distances from the source. Reverberation and multi-paths "stretch" the signal from its original 10 ms to sometimes seconds, at long ranges (Guerra et al. 2011). Sometimes, noise levels do not have a chance to return to ambient in the 10 s between airgun shots, since there is still reverberation from the previous shot (Guerra et al. 2011). MV signals can also be lengthened or stretched in time with increasing distance from the source, but such stretching would be proportionally less than for airgun pulses, since MV signals are longer in duration initially, close to the source (LGL and MAI 2011). MV signals would likely fade more quickly into the background ambient noise levels.

MV should be field-tested for impacts on a wide range of sensitive marine taxa, something which should ideally happen in tandem with operationally testing various MV designs. As with other noise-reduction measures from seismic surveys, the development of MV could be greatly expedited with encouragement and pressure from regulatory governmental agencies (Duncan et al. 2017).

Because of the need to better control the output of marine seismic sources and to reduce their environmental footprint, ExxonMobil, Shell, and Total sponsored the Marine Vibrator Joint Industry Project (MV JIP) in 2011, supporting the development of two separate marine vibrator technologies. To date, they have not yet finished all stages of testing these devices, despite promising much earlier dates for commercial availability. If regulators were to insist on use of quieter alternatives to airguns, I believe these would be available very quickly, but regulators feel they cannot require a technology that is not available yet, so it becomes a chicken-and-egg argument.

The Joint Industry Program on E&P Sound & Marine Life (SML JIP) also issued a Request for Proposals due May 2019 to determine the environmental impact of prototype Marine Vibrator technology. Of interest is the impact of MV output signals on marine mammal auditory masking and behavioral responses.

It is very difficult to get more information on technological alternatives to airguns, as much is proprietary and still under development. The Marine Vibrator that is already being used in shallow and transition zones is Geokinetics AquaVib Marine Vibrator. It works better in water depths less than 5 m than airguns do. Teledyne Marine has an airgun called the eSource that was developed by Bolt Technology Corporation and WesternGeco. It releases air more gradually than the conventional airgun so that it attenuates or reduces the higher frequencies while optimizing frequencies in the seismic band of interest, in order to minimize the effects on marine mammals. The eSource contains three sources in one tunable package, and two models are available. The advantage with this alternative is that it does not require any retrofitting of the seismic vessels, as MV does, and can be used as a conventional airgun would be. The disadvantage is that the approach may be too piecemeal and not comprehensive enough, as other potentially damaging characteristics of airgun pulses remain. Wolfspar from BP uses very low frequencies of around 1-2 Hz together with ocean bed nodes. It is used to better imagine an oil or gas reservoir, particularly through salt layers.

Monitoring technology

To assess the population density, abundance, and distribution of marine life before, during, and after seismic surveys, monitoring, especially ahead of time, of the proposed survey area should be carried out with fixed acoustic detectors (buoys, bottom recorders, etc.) or mobile gliders.

Infrared (IR) or thermal imaging shows promise in detecting warm-blooded marine life, such as whales and dolphins, which can help in nighttime monitoring, especially of baleen whales (Zitterbart et al. 2013). It is not meant to replace Marine Mammal Observers but to supplement them by alerting them to possible whale blows (exhalations). It also does not function well in some conditions, such as fog, or with species that do not spend much time at the surface or with obscure blows (Zitterbart et al. 2013). It does not work well on smaller whales, even ones the size of minke whales, and is very expensive. It seems to work best in polar regions.

Passive Acoustic Monitoring (PAM) should be used anytime there are vocal species in the area, during daytime or nighttime. Towed arrays or other suitable technologies with enough bandwidth to be sensitive to the whole frequency range of animals expected in the area should be used to improve detection capabilities. PAM should be mandatory for night operations or when visibility is scarce. However, PAM may be inadequate mitigation for night operations if species in the area are not vocal or easily heard.

BEP for Seismic Airgun Survey Noise

As mentioned above, probably the most effective mitigation for seismic airgun surveys is to: a) separate the seismic surveys from areas rich in marine life and sensitive species; and b) to lower the source level (quiet the noise). In order to separate seismic surveys from marine life, however, there must be good, current knowledge of the abundance and distribution of that life. Therefore, baseline studies of biological abundance and distribution must occur at least a year, preferably two, in advance of seismic surveys. These must be of sufficient quality and statistical power to meaningfully mitigate impacts. Sensitive and important habitats and seasons (spawning, breeding, feeding, etc.) should be avoided, and not just for marine mammals. Turtles, fish, and invertebrates must be included in mitigation and monitoring wherever possible. Acoustic refuges of still quiet habitat should be established, and Marine Protected Areas should be managed for noise and include acoustic buffer zones around them, considering the possible impact of long-range noise propagation.

The ACCOBAMS (Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area) Resolution 4.17, Guidelines to Address the Impact of Anthropogenic Noise on Cetaceans in the ACCOBAMS Area, are very close to BEP for seismic airgun survey noise. The below guidelines are based on the ACCOBAMS guidelines:

a) Baseline studies of biological abundance and distribution of sensitive species, including turtles, fish, and invertebrates, must occur at least a year, preferably two, in advance of seismic surveys. These must be of sufficient quality and statistical power to meaningfully mitigate impacts.
b) Seismic surveys should be planned so as to avoid key habitat and areas of density of marine life, so that entire habitats or migration paths are not blocked, so that cumulative seismic noise is limited within any particular area, and so that multiple vessels operating in the same or nearby areas at the same time are specifically regulated or prohibited.
c) Seismic surveys should not be allowed to proceed without some proof of efficacy of the mitigation measures used and for all sensitive species.
d) Acoustic refuges of still quiet habitat should be established, and Marine Protected Areas should be managed for noise and include acoustic buffer zones around them, considering the possible impact of long-range noise propagation.
e) Transparent, public notification of when and where seismic surveys will take place as soon as this is known by the operators (months in advance).
f) Use of the lowest practicable source power and have this verified by independent evaluators.
g) Limit horizontal propagation by adopting suitable array configurations and pulse synchronization and eliminating unnecessary high frequencies.
h) Airguns should not be operated for any reason outside the permitted project area.
i) Adapt the sequencing of seismic lines to account for any predictable movements of animals across the survey area and avoid blocking escape routes.
j) Modelling of the generated sound field in relation with oceanographic features (depth/temperature profile, water depth, seafloor characteristics) to dynamically set the Safety or Exclusion Zone (EZ). Verify models of the EZ in the field. EZ should be at minimum 500 m but may be larger depending on the propagation.
k) Continuous visual and passive acoustic monitoring (PAM) by a specialized team of Marine Mammal Observers (MMOs) and PAM operators to reduce the risk that animals are not in the Exclusion Zone before turning on the acoustic sources and while sources are active.
l) Equipment for visual monitoring should include suitable binoculars and big eyes to be used according to the monitoring protocol.
m) Airgun surveys should be prohibited at night, during other periods of low visibility, and during significant surface-ducting conditions, since mitigation tools are likely inadequate to detect and localize sensitive marine life. Because of the impact of adverse weather conditions on the visual detection of animals, seismic surveys during unfavourable conditions (over Beaufort Wind Speed of 3) should be prohibited as well. Only if Passive Acoustic Monitoring (PAM) is proven as effective in detecting sensitive marine life as PAM together with MMOs, should seismic surveys in poor visibility and at night be allowed.
n) Passive acoustic monitoring (PAM) (towed array technology or other suitable technologies with enough bandwidth to be sensitive to the whole frequency range of sensitive marine life

expected in the area) should be used to improve detection capabilities. PAM may be inadequate mitigation if animals in the area are not vocal or easily heard.

o) At least two dedicated Marine Mammal Observers (MMOs) should be on watch at one time on every operative ship; shifts should be organized to allow enough rotation and resting periods for MMOs. In the case of acoustic monitoring, at least one PAM operator should be on watch and shifts should be organized to allow 24/24h operation, unless automatic detection/alerting systems are proven to be as effective as PAM operators. Standardized tests (written and in the field) for MMOs and PAM operators, used worldwide, should be developed to ensure MMOs and PAM operators pass standard qualifications.

p) Before beginning any emission there should be a dedicated watch of at least 30 minutes to reduce the risk that animals are within the EZ.

q) Establish a minimum pre-clearance zone (i.e., pre-ramp up watch zone) that extends 1000 m from the outer perimeter of the airgun array(s).

r) Extra mitigation measures should be applied in deep water areas if beaked whales are expected or if habitats suitable for beaked whales are approached: in such a cases the watch should be at least 120 minutes to increase the probability that deep-diving species are detected.

s) Every time sources are turned on, there should be a slow increase of acoustic power (ramp-up or soft start) to increase the chances that animals might leave the ensonified area (the effectiveness of this procedure is still debatable).

t) The beginning of emissions should be delayed if sensitive species are observed within the exclusion zone (EZ) or approaching it. Ramp-up may not begin until 30 minutes after the animals are seen to leave the EZ or 30 minutes after they are last seen (120 minutes in case of beaked whales).

u) There should be a shut-down of source(s) whenever a sensitive species is seen to enter the EZ and whenever aggregations of vulnerable species (such as beaked whales) are detected anywhere within the monitoring area

v) If more than one seismic survey vessel is operating in the same area, they should maintain a minimum separation distance (dependent on propagation) to allow escape routes between sound fields.

w) Data sharing among seismic surveyors should be encouraged to minimize duplicate surveying. Also, if old seismic data can be usefully re-analyzed using new signal processing or analysis techniques, this should be encouraged. Duplicated surveys need to be justified.

x) An quantitative analysis of cumulative and synergistic impacts not just of noise but of all anthropogenic threats over time should be conducted as part of a thorough Environmental Impact Assessments (EIAs) following the CMS Family Guidelines on EIAs for Marine Noise-Generating Activities, including consideration of historical impacts from other activities (shipping, military, industrial, other seismic) in the specific survey area and nearby region. Databases and noise registries should be developed to allow such analyses.

y) A system of automated logging of acoustic source use should be developed to document the amount of acoustic energy produced, and this information should be available to noise regulators and to the public

z) Mitigation should include monitoring and reporting protocols to provide information on the implemented procedures, on their effectiveness, and to improve data on biological abundance and distribution, as well as to examine impacts from seismic survey noise. Monitoring should be proven to be statistically powerful enough to detect subtle impacts, strandings, fish kills, etc. BDA (Before During After) or BACI (Before After Control Impact) studies to examine impacts must also contain power analyses to show whether possible impacts would be detectable or not. Impact and biological baseline studies should include more fish, turtles, and invertebrates. All biological and impact data collected for mitigation should be publicly available.

aa) MMO and PAM reporting should be standardized so that data can be harmonized across all seismic surveys worldwide for maximum statistical power.

bb) During operations, existing stranding networks in the area should be alerted; if required, additional monitoring of the closest coasts and for deaths at sea should be organized.

cc) A biological survey after the seismic survey is finished should be carried out to verify if changes in the abundance or distribution of species or anomalous deaths occurred.

dd) In the case of strandings, deaths at sea, or abnormal behavior possibly related with the operations, any acoustic emission should be stopped and maximum effort devoted to understanding the causes of the deaths or abnormal behavior.

BAT for Pile Driving Noise

Noise levels

Pile driving is used for the construction of offshore windfarms in addition to the construction of structures such as piers and bridges. Pile-driving (1000 kJ hammer) levels are around 237 dB re 1 µPa at 1 m, with a bandwidth of 100–1000 Hz (Hildebrand 2009). Again, though more energy is in the lower frequencies, pile driving noise extends into the tens of kHz.

Impacts

Harbour porpoise avoid pile driving out to a mean distance of 17.8 km. At 22 km, this avoidance was no longer apparent. Porpoise activity and possibly abundance were reduced over the entire 5-month windfarm construction period (Brandt et al. 2011). Teilmann and Carstensen (2012), in a long-term, 10-year study, showed that harbour porpoise echolocation activity (a sign of foraging) significantly declined inside an offshore windfarm and did not fully recover after 10 years. Blue mussels (Spiga et al. 2016; Roberts et al. 2015) and seabream (Bruintjes et al. 2017) showed signs of stress from pile driving. Swimming and schooling behaviour was also affected by piling in cod and sole (Mueller-Blenkle et al. 2010), sprat and mackerel (Hawkins et al. 2014), and juvenile seabass (Herbert-Read et al. 2017).

Largely due to the German government setting an action-forcing standard for better systems, major progress in quieting technology has been made for pile driving. In 2004, The German Federal Maritime and Hydrographic Agency introduced noise guidance values of 160 dB re 1µPa^2 s (SEL) or 190 dB re 1 µPa (peak) at a distance of 750 m in the licenses of offshore wind farms within the German EEZ. In 2008, these became mandatory and were successfully applied in 2013, reaching state-of-the-art reliable compliance despite increasing pile diameters and water depth through 2018. No offshore windfarm in German waters has since been constructed without complying with the noise limits. In 2013, the German Federal Agency for Nature Conservation also published its Sound Protection Concept. In addition to technical mitigation measures, pile driving companies purposely use lower piling/hammer energies to stay under the German noise limits. Belgium also has noise limits, using a threshold of 185 dB (peak) and no SEL limit. Koschinski and Lüdemann (2013) detail technical noise mitigation measures for pile driving as well as alternative low-noise foundation concepts and analyze their applicability. Table 1 (below), reprinted from Koschinski and Lüdemann (2013), summarizes various noise mitigation measures, their noise reduction potential, and development status (similar to Technology Readiness Level for shipping noise). Table 2 (below), also reprinted from Koschinski and Lüdemann (2013), lists several alternative low-noise foundation types that can secure wind turbine piles without impact pile driving, making them quieter.

Table 1: Noise mitigation measures for impact pile driving, their reduction potential, development status und next steps (n. s. = not specified; SEL = Single event sound pressure level; peak = peak level)
Note: Noise reductions specified as broadband levels are not directly comparable to those specified as mitigation levels in singular third octave bands!

	Mitigation measure	Noise reduction	Development status[1])	Questions, next steps
Bubble curtains	Big bubble curtain	• FINO 3: 12 dB (SEL), 14 dB (peak) (GRIEßMANN et al. 2010), OWF *Borkum West II*: 11-15 dB (SEL), 8-13 dB (peak) (BELLMANN 2012) • Double big bubble curtain (two half-circles): 17 dB (SEL), 21 dB (peak) (HEPPER 2012)	• Proven technology, potential for optimisation • German160 dB threshold level can be met under certain environmental conditions	• Practical application in several commercial offshore wind farms (OWFs) • Application with larger pile diameters at larger water depth • Potential for optimization with respect to effectiveness and handling
	Little bubble curtain (several variations)	• Layered ring system (OWF alpha ventus): 12 dB (SEL), 14 dB (peak) (GRIEßMANN 2009); OWF Baltic II: 15 dB (SEL) (SCHULTZ-VON GLAHN 2011) resp. 11-13 dB (SEL) (ZERBST & RUSTEMEIER 2011) • Confined little bubble curtain (ESRa): 4-5 dB (SEL) (WILKE et al. 2012)[2]) • Little bubble curtain with vertical hoses (SBC): 14 dB (SEL), 20 dB (peak) (STEINHAGEN 2012)	• Pilot stage with full-scale test completed	• Practical application, currently no specific projects known
Isolation casings	*IHC Noise Mitigation System*	• ESRa project: 5-8 dB (SEL) (WILKE et al. 2012) 2) • FLOW-project: OWF *Nordsee Ost:* 9 dB (SEL), Ijmuiden: 11 dB (SEL) • OWF *Riffgat*: 17 dB (SEL) (GERKE & BELLMANN 2012)[3])	• Pilot stage completed • First application at commercial OWF *Riffgat* • 160 dB threshold level can be met with small and intermediate piles at shallow depths	• During further applications a direct comparison with and without mitigation system is required • Application at greater water depths and with larger diameters
	BEKA-Shells	• ESRa project: 6-8 dB (SEL) (Wilke et al. 2012) 2)	• Pilot stage completed	• Full-scale test under offshore conditions • Currently no commercial application known
Cofferdam	Cofferdam	• Aarhus Bight: 23 dB (SEL), 17 dB (peak) (THOMSEN 2012)	• Pilot stage for free-standing system completed • First application in commercial projects planned	• Full-scale test for larger monopiles (∅ about 5 m) • Practical application in commercial projects *HelWin alpha*, *BorWin beta* and *Sylwin alpha* planned • Further development of telescopic system
	Pile-in-Pipe Piling	• Model: 27 dB (SEL) (FRÜHLING et al. 2011)	• Validated concept stage	• n. s.

	Mitigation measure	Noise reduction	Development status[1])	Questions, next steps
Others	Hydro Sound Dampers (*HSD*)/ "encapsulated bubbles"	• *ESRa* project: 4-14 dB (SEL) (WILKE et al. 2012) [2]) • OWF *London Array:* n. s. • Feasibility study US: in singular third octave bands up to 18 dB (no broadband value given) (LEE et al. 2012)	• Pilot stage, application in commercial OWF *London Array*	• Further offshore test (OWF *Dan Tysk)* planned for 2013 • Optimisation of *HSD* elements • Additional *HSD* elements and net-layers • Tests to reduce seismic influence
	Prolongation of pulse duration	• Model: 4 dB (SEL), 9 dB (peak) (ELMER et al. 2007a) • Schall 3: Model of *MENCK* test pile: 5 dB (SEL), 7 dB (peak). Model of *FINO 3* pile: 11 dB (SEL), 13 dB (peak) (NEUBER & UHL 2012) • Measurement of coiled steel cable as piling cushion: up to 7 dB (SEL) 4) (ELMER et al. 2007a) • Measurement of piling cushions from Micarta: 7-8 dB , Nylon 4-5 dB 5) (LAUGHLIN 2006)	• 160 dB threshold level can be met with very small pile diameters, used as a means of protecting the equipment • Experimental stage for larger piles (numerical models and simulation)	• n. s.
	Modification of piling hammer	• n. s.	• Experimental stage	• Completion of research project *BORA* and publication of results

[1]) With regard to North Sea offshore conditions and water depths of about 40 m

[2]) For the interpretation of the results achieved in the *ESRa* project, the problems outlined in chapter 4.1 have to be taken into consideration

[3]) Calculation of noise reduction is based only on the predicted value of noise emission without mitigation system, see chapter 4.3.4

[4]) *FINO 2* platform (pile diameter 3.3 m)

[5]) Cape Disappointment (pile diameter 0.3 m)

Table 2: Low-noise foundations, their reduction potential, development status und next steps (n. s. = not specified; Leq = equivalent continuous sound level)

	Method / project	Noise emission during construction	Development status[1])	Questions, next steps
Vibratory pile driving	Vibratory pile driving	• Sound level reduced by about 15-20 dB compared to impact pile driving (ELMER et al. 2007a) • North Sea, OWF *alpha ventus*: broadband sound level 142 dB at 750 m from source; but high tonal component (BETKE & MATUSCHEK 2010), OWF *Riffgat*: 145 dB Leq (GERKE & BELLMANN 2012) • Number of pile strikes reduced	• Proven technology for small piles and low anchoring depths and prior to the actual impact pile driving (OWF *Riffgat*)	• `Vibratory pile driving applicable to entire anchoring depths? • Is the same stability under load achievable?
Foundation drilling	*Ballast Nedam*	• n. s.	• Concept stage • Technical feasibility proven (VAN DE BRUG 2011)	• Pilot stage planned at *FLOW* project
	Herrenknecht	• Measurement at watered shaft in Naples: 117 dB (SEL) at 750 m (AHRENS & WIEGAND 2009)	• Technical feasibility proven (AHRENS & WIEGAND 2009) • Onshore tests • Prototype under construction	• Investigations of carrying capacity • Construction of prototype for 2013 • Nearshore test 4th quarter 2013 • Offshore prototype-test beginning of 2014
	Fugro Seacore	• n. s.	• Proven technology for certain types of ground (rock, sand- and limestone) and in combination with impulsive pile driving	• Investigations of resulting stability under load when founded without impulsive piling • Applicability to sandy sediments?
Gravity base foundations	Gravity base foundations	• No specific measurements available • Noise emissions during ground preparation works (if required) probably lower than during impulsive pile driving	• For offshore wind turbines: proven technology at water depths ≤ 20 m, pilot stage for deeper water • Onshore full scale test foundation • For oil & gas: proven technology also at greater water depths	• Question of detail on scour protection
Floating wind turbines	Floating wind turbines in general	• No specific measurements available • Noise emissions probably lower than during impulsive pile driving	• Oil and gas platforms: proven technology • Offshore wind turbines: experimental or pilot stage	• Details of anchorage • Operational noise of wind turbines possibly louder than with other foundation types
	HYWIND	• n. s.	• Pilot stage, Full-Scale-test in Norway, two year research project completed	• n. s.

Floating wind turbines	*Blue H*	• n. s.	• Pilot stage • Experimental stage with 75% model completed	• Subproject continued in a different form by *Blue H Engineering* (see below)
	Blue H Engineering	• n. s.	• Conceptual stage for 5 MW turbines	• Prototype planned for 2016
	GICON-SOF	• n. s.	• Experimental stage • Development of planning tool for technical, ecological and economic design-basis for prospected research facility • Investigations in wave channel completed	• Prototype planned for 2012
	WindFloat	• n. s.	• 2011: Prototype erected in Portugal with Vestas V80	• 5 more turbines planned
	Sway	• n. s.	• Experimental stage completed: Dynamic simulations completed • Pilot stage: prototype approved	• Prototype planned for 2013
	WINDSEA	• n. s.	• Experimental stage with 1:40 model in wind- and wave-channel completed	• Search for investors
	INFLOW	• n. s.	• Experimental stage • Onshore demonstration model at a scale of 1:2 completed (output 35 kW)	• Prototype planned for 2013
	WINFLO	• n. s.	• Ongoing model-tests • Prototype under construction	• Prototype planned for 2013
	Poseidon 37	• n. s.	• Prototype (37 m width) with 3x11 kW output completed	• Larger prototype (80 m width) planned for 2015 • Subsequent prototype of 110 m width planned for 2016/2017
Bucket foundations	Bucket foundation for transformer platform	• n. s. • Noise emissions during suction dredging probably lower than during impulsive pile driving	• Oil and gas platforms: proven technology	• Construction of converter platforms at commercial OWFs *Veja Mate* and *Global Tech 1*
	Bucket foundation for offshore wind turbine		• Pilot stage for monopod: prototype at Frederikshavn/DK • Concept stage for Tri-jacket • Experimental stage for asymmetric three-legged construction (model tests completed)	• Tri-Jacket: full-scale prototype planned at virtual test field • Asymmetric three-legged construction: full-scale prototype planned

* With regard to North Sea offshore conditions and water depths of about 40 m

A more recent report was provided by Verfuss et al. (2019) who reviewed noise abatement systems (NAS) for offshore windfarm (OWF) construction noise and how applicable these were for Scottish waters. They found NAS could reduce sound exposure levels by 10 to 18 dB using a single system and up to 28 dB using a combination of systems. Operational experience of OWF construction in depths deeper than 50 m is lacking though. The report (Verfuss et al. 2019) provides:

- "A description of the status of currently commercially available and frequently used NAS and those under development,
- A summary of the experience of NAS users and NAS providers with regard to the logistical requirements and limitations for the deployment and operation of these NAS,
- A review of the environmental limitations that may influence the deployment and operation of NAS,
- A review of the direct cost implications associated with the use of NAS,
- A review of the noise reduction efficacy of NAS, specifically with reference to the marine species inhabiting Scottish waters."

The main findings of Verfuss et al. (2019) were that:

- 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 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 depths 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.

Some of these noise abatement systems are described below.

Recently, piles with diameters of 7-8 m are being used compared with initial piles which were only 2.5 m in diameter. 12-m-diameter piles are even proposed for the future. Different types of foundations are used for different substrates and water depths. Driven piles are used for sand, such as in the southern North Sea, whereas drilled piles require a higher substrate strength.

It is important to note that sound can enter the substrate from pile driving, travel through the substrate, and emerge into the water column at a fair distance from the pile driving ("ground-coupling effect"). Thus, mitigating the noise emitted through the water near the pile will not necessarily solve the problem if the noise emerges beyond a bubble curtain, for instance. Primary noise reduction, occurring at the source, has the advantage of solving this substrate transmission problem. Secondary noise reduction occurs once the sound has already been transmitted into the water or substrate.

Gravity-Based Foundations

The most effective way to reduce noise at the source is to use a foundation that does not require pile driving. Gravity Based Foundations are most suitable for depths of 30-50 m (they can also be designed for deeper waters and have been used extensively by the oil and gas industry in depths of up to 300 m), bedrock, consolidated sediments, and areas with large buried boulders. Their disadvantage is that they may have a relatively larger impact on benthic life, since at least some types remove the upper 6 m of the seabed. Suction Caisson/Bucket Foundations are used for low substrate strength (sand or clay, although layered soil may also be feasible) and a relatively flat seabed is preferable; little seabed preparation is required. Suction caissons are more suitable for deeper waters and were originally developed in the 1990s for oil and gas applications. It is anticipated that piles will be placed in >40 m water depth for offshore wind applications.

Vibropiling

Vibration pile-driving or vibropiling could be a promising alternative to conventional pile driving. The advantages include less noise, faster (so less exposure time), more reliable, fewer lifts and handling, fewer vessels on site, material saved on the monopile, less mitigation for noise, and there is considerable offshore experience using it, but no full-scale offshore wind park has yet been installed solely by vibropiling. Vibration piling is 10-20 dB lower in peak levels compared to mitigated pile driving. Levels fall to 140 to 145 dB in 8 km for pile driving vs. 1.5-3 km for vibropiling. The affected area is 7-28 sq km for vibropiling vs. 201 sq. km for pile driving. However, vibropiling causes very low frequencies so further mitigation using a bubble curtain wouldn't help reduce the noise. The noise peaks arise from rattling from the loose connections of the vibrohead.

BLUE Piling
This uses a large water column thrown up and down and avoids the use of moving parts. The pile fills up with sea water and is a dead weight, which is pumped into the hammer. When it falls back, it delivers its heaviest load. The water is then drained back into the sea and the empty hammer is placed back on the vessel. The gradual increase in force reduces underwater noise and reduces fatigue. The duration is 100-200 ms vs. 4-9 ms for a normal hammer. The pile is more "pushed" than driven, but the technology uses the same methodology as a conventional pile driver. There is not much stress on the hammer, and no bending or stress fluctuations occur in the steel as with a conventional hydraulic hammer. As a result, this could be a cheaper alternative, reducing both noise and fatigue. Piling could possibly also be done faster. The pile is removed just using water pressure which is environmentally better. Many factors can be varied so as to modify the force profile to the actual conditions. About 95% of the blows fall below the 160 dB re 1µPa² s (SEL) German threshold and 100% fall below the 190 dB re 1 µPa (peak) SPL German threshold, both at 750 m. Levels are 20 dB lower in SEL than conventional piling, and the SEL(single strike) is 16 dB lower. It is possible that piles may be able to be installed without any noise mitigation. The hammer capacity and reliability still need to be improved. The hammer is expected to be commercially available in 2020. The aim is to overcome soil resistance and require less blows.

Smart Pile Driving
Smart Pile Driving by Hydrohammer determines the necessary piling energy and the optimum hydrohammer type. The piling approach (energy, repetition rate) is adjusted based on real time measurements. By thoroughly analyzing each case, one can just use the minimum energy needed to keep the pile penetrating. One can first use a high blow rate, with low energy, gradually shifting to a low blow rate with high energy during the piling process. Using a low inclination angle is important. If the angle is too large, the pile doesn't penetrate. Using a low angle of inclination when installing the piles shortens the installation period. PULSE (Piling Under Limited Stress) achieves 6-9 dB SEL and 10-12 dB SPL noise reduction, as well as a 60% reduction in fatigue and stress on the equipment.

Drilling
BAUER has several offshore foundation drilling techniques for various substrate conditions.

1) MIDOS-Pile combines mixing and drilling technology to install a structural pile. The drilling and mixing tool is full of grout. This can be used in mainly sandy substrates but also clay and rock. The substrate is mixed with cement and creates a slurry that is injected during drilling. The structural capacity is higher so shorter and smaller piles can be used. XXL monopoles are too big for this technology, however. There was considerable bearing capacity when tested in loose, silty, sandy soil. The noise is much lower than piling and the structural capacity is better. The substrate must be mixable, e.g. sand with some clay.
2) Dive Drill Technology is used for the installation of drilled and grouted piles. Drilling occurs inside a casing and is replaced with the pile. A temporary casing is installed using the Bauer Dive Drill. Once the borehole is finished, the pile is installed, grouted, and then the temporary casing is recovered. Dive Drill Technology installs piles in fully cased boreholes and is suitable for all soil conditions including hard rock. It makes pile driving in marginal soil unnecessary.
3) BSD 3000 is for drilling piles in rock. The pile is installed and grouted afterwards. In 200-300 m, the noise is under background noise (125 dB rms).

Push-in and helical piles

Push-in and helical piles are two concepts for silently driven piles. Both concepts can serve as an alternative for jacket foundation piles and are therefore suitable for deep water wind turbine foundations. Both have been proven onshore. The push-in pile foundation uses a static force to drive piles into the seabed, and the helical pile foundation uses a rotating motion to drive piles fitted with several helical blades into the soil. Helical piles don't need to be as long and have shallow penetration. Both concepts are fully silent, but will require special tools and in the case of the helical pile, an interface with the installation vessel using Dynamic Positioning.

Suction Bucket Jackets

Suction Bucket Jackets (SBJ) are connected rigidly to a structure, installed in shallow water (<100 m), and have a large overall footprint. They penetrate the substrate by using self-weight. The suction on the ends of the legs pumps out the water and the structure is sucked into the ground. The noise is barely over background noise. SBJ is a deeper water solution and used in many substrate conditions, but not very hard soils, soft soils, or rocks. There can be no large sand waves or high seabed mobility in the area of installation. Installation does not require mechanical force. Water depths of less than 15-20 m may not be suitable as the weight of the water is needed to stabilize the structure. There is an impact on soil and benthic biotypes.

Mono bucket foundation

The mono bucket foundation is a monopile foundation with a suction bucket seabed interface. Installation is simple, fast (<12 hrs.) and noise free. It is used in sandy soils, clay or combinations thereof. Installation can be done in shallow water of <3m. In the whole life cycle, these foundations can recycle 200,000 tons of carbon per project.

Crane-free gravity foundations

Crane-free gravity foundations are a noiseless foundation technology. Dredging is usually not required, they are not just used for some soil types, and they do not cover much of the seabed, though more than conventional foundations. It is not unproven technology nor is it expensive. It is more cost-effective at larger depths and bigger turbines. The foundations can be installed with or without cranes. They are self-floating so do not need large vessels, there is no lifting, and less dependency on good weather. There is no sound emission from the subsea installation process, and no deep penetration of seabed. The base diameter is 31-34 m. Foundations are made from concrete. Two tow vessels (tugs) pull the vertical pile through the water and they can be installed in seas up to 2 m. Installation takes 4 hrs. The foundation is then deployed by letting seawater fill the hollow foundation and it is thereafter fixed to the seabed by its own ballasted weight. It is placed on a filter layer with scour protection. Skirts improve load resistance, reduce dimensions, avoid dredging, and reduced weight. The ballast is sand or gravel placed inside the foundation after it is placed on the seabed. Ballast is used so the foundation can withstand highest turbine and wave loads. Gravity-based foundations can be designed for lifespans of 50 years or more. They need a minimum water depth of 10 m.

Floating wind turbines

Semi-submersible floating wind turbines have been deployed in some of the roughest seas of the Atlantic where they survived 17 m waves. Just one river tug is needed to place the turbine and it can be towed up to 500 km. Many waters are too deep for non-floating structures. These turbines can be used in all different sediment types. The anchors are fully retrievable and no effect on marine life has been observed.

One example of a floating offshore wind foundation is a tension leg platform (TLP) which emits minimal noise. It is best used in 30-40 m water depth, where monopoles are not as competitive. Floating foundations do not rely on a fixed connection to the seabed. Rather, different anchor types such as gravity anchors, suction buckets or also drilled or driven piles can be used to hold the floating substructure and the wind turbine on top in place. Suction buckets are used most often as anchors. Drag anchors impact the seabed, though they are quiet. Mooring cables come in various types (taut leg, tension leg mooring, etc.). Special vessels like jack-up barges are not required. Just small tugboats are needed, and then a ballast gravity anchor is used and the foundation is dropped to the seabed. There is little assembly time, a one-step installation, and little seabed preparation is necessary.

Secondary noise mitigation

Different secondary noise mitigation technologies are applied close to the pile compared to those used further away. Examples of secondary noise reduction include:

1) Noise Mitigation Screen (IHC) which is used for piles under 8 m diameter (though it is being discussed in the context of 10.3-m piles in the U.S.) and under 40 m water depth. This system is a double-walled steel pipe with an air gap between the two layers. A multi-layered bubble curtain is also used in the center around the pile. A disadvantage is the ground coupling effects. Noise reduction is independent of water depth. Noise reductions of 13-16 dB SEL are achieved even at 40 m water depth. It is ready for offshore application.

2) Hydro Sound Damper (HSD) consist of small gas-filled or foam balloons affixed to fishing nets which fish can swim through and which doesn't affect the water flow. HSD baskets or a net sleeve are dropped down into water around the pile and then collapse back up when the pile is installed and the basket is returned. Noise reduction is independent of water depth. This can achieve up to a 23 dB SEL noise reduction (93% of the noise is gone) and noise reductions of 10-12 dB SEL are achieved even at 40 m depth. It can be tuned to the resonant frequencies. Overall, the system works for water depths of 40-60 m, pile diameters of 8-13 m, pile lengths of 80 m, and is easily adaptable, weighing very little, and is not affected by water currents. A disadvantage is still the ground coupling effects. This technology requires a project-specific design but is ready for offshore deployment. It does not need compressed air so there is no carbon footprint.

3) AdBm-Noise Abatement System uses rugged Helmholtz resonators whose acoustic properties can be modified or "tuned" to optimally treat noise. These resonators simply need to surround the sound source, and once they are in place, the resonators will passively absorb the noise. They have been designed to work to at least 400 m. The system is kept in place for the duration of the pile installation process.

4) Double Big Bubble Curtain is a set of two large perforated flexible tubes that are positioned in concentric rings around the construction zone. Air is pumped through the tube and released through the perforations delivering a continuous flow of bubble around the periphery the construction zone. Big bubble curtains can be used for piles of at least 10.3 m in diameter (i.e. 10 MW). The use is independent of foundation design and installation vessel. The noise reduction depends on water depth, and current/direction/shape. The noise reduction may be, for example, 14 dB SEL at 25 m, but only 9 dB SEL

at 40 m depth, though this can be overcome with modifications such as combining it with other noise mitigation systems like HSD. The SEL can be reduced an additional 2.5 dB by halving the hammer energy.

The great variety of quieting technologies and noise abatement systems for pile driving is in stark contrast to the lack of innovation that is occurring for quieter alternatives to the seismic airgun. This may be due to offshore windfarms being a relatively new development compared with seismic airgun surveys, but it does raise questions. Certainly having governments, like the German, Dutch, and Belgian ones, that are prepared to regulate the construction of offshore windfarm construction for noise, mainly due to the noise-sensitive and protected harbor porpoise, helps, as do European laws but it is high time that regulators insist on quieter alternatives to airguns, something that seems well within technological capabilities. After all, explosions on land to search for hydrocarbons were replaced with vibroseis because explosions were no longer acceptable to humans.

BEP for Pile Driving Noise

Most of the mitigation for pile driving noise is through the use of quieting technologies rather than Best Environmental Practices. However, there is some debate whether marine life should be purposely displaced at the start of pile driving. This can be accomplished by using Acoustic Deterrent Devices. FaunaGuard is one such device that has been used since research showed pinger and seal scarers produced more displacement than was necessary. Another possibility is using the mitigated pile driving noise itself but initially at lower energy and/or repetition rate (ramp up or soft start) to give marine life a chance to remove themselves from the area. This practise has the advantage that it prevents introducing yet more unnecessary noise into the environment, something which should generally be avoided. As with seismic surveys, MMOs and PAM operators can also be used to reduce the risk of exposing marine life to dangerous sound levels. Visual and acoustic monitoring should be used in combination 24 hours a day to maximize the probability of detection of wildlife, including at night and during periods of poor visibility. If this monitoring is deemed insufficiently effective, the pile driving should not be allowed during nighttime and periods of poor visibility.

Some examples of best practices for pile driving that have been developed in the United States for the highly endangered right whale are listed below. The full document is available at:

https://www.nrdc.org/sites/default/files/best-management-practices-north-atlantic-right-whales-during-offshore-wind-energy-construction-operations-along-us-east-coast-20190301.pdf

- Construction activities with noise levels that could cause injury or harassment in marine mammals must not occur during periods of highest risk for priority species.
- During construction, developers should commit to minimizing impacts of underwater noise on priority species to the full extent feasible through: (i) the consideration and use of foundation types and installation methods that eliminate or reduce noise; and (ii) the use of technically and commercially feasible and effective noise reduction and attenuation measures, including the use of the lowest practicable source level.

- Developers should commit to carrying out scientific research and long-term monitoring in lease areas to advance understanding of the effects of offshore wind development on marine and coastal resources, and the effectiveness of mitigation technologies (e.g., noise attenuation and thermal detection). Science should be conducted in a collaborative and transparent manner, utilizing recognized marine experts, engaging relevant stakeholders, and making results publicly available. Developers should coordinate with regional scientific efforts to ensure results from individual lease areas can be interpreted within a regional context and contribute to the generation of regional-scale data, which is required to address questions related to population-level change and cumulative impacts.

As noted above, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) adopted the *Sound Protection Concept.* In it, in addition to the technical noise reduction systems required, the following are also mandatory:

- Modelling of sound level emission for each specific wind farm project;
- Restrictions regarding the maximum duration of a piling operation for a single pile;
- Restrictions regarding the maximum energy used to drive the piles;
- Application of deterrents and ramp-up procedure;
- Measurement and documentation of SEL_{05} during the whole installation process. (The SEL_{05} percentile level is used as reliable and standardized evidence for compliance with threshold values and is the level exceeded 5% of the time over the total piling period to account for cumulative effects due to multiple blows for driving piles to final penetration depth);
- Monitoring of harbour porpoise activity in the vicinity of construction sites;
- Requirements regarding the percentage of area which is allowed to be affected also with a reference to protected areas or areas and seasons of biological significance.

Conclusions

One of the difficulties in responsibly managing ocean noise pollution is the challenge in detecting the ecosystem and population consequences of underwater noise. There is sufficient evidence that impacts are occurring in at least 130 marine species (around 100 fish and invertebrate species alone—Weilgart 2018), but being able to ascertain exactly to what degree, in which contexts, for which species, and at what sound types and levels these impacts occur remains imprecise. Because of the large natural variability in ocean systems (e.g. in currents, prey availability, chemistry), detecting human-caused changes in ecosystems and populations in the first place is a daunting task. The ocean is not a controlled laboratory. On top of that, isolating changes that are solely due to ocean noise pollution and not other human-caused stressors such as climate change, overfishing, and toxins, is formidable. As such, it makes more sense to take a more precautionary approach, one of simply turning down the volume of ocean noise pollution. Especially in cases where there are ancillary benefits of quieting, such as reducing greenhouse gas emissions by finding the overlap between greater efficiency and less underwater noise in shipping, and by encouraging technological innovation through quieter technological alternatives to airguns and by quieting pile driving, our efforts are likely more effective using this approach. Keeping more fossil fuels in the ground would also reduce our need for seismic surveys and cut greenhouse gases. With humans, we don't find the precise point where noise is just tolerable to newborns in Neonatal Intensive Care Units, we don't fund countless studies on exactly how stressed and disturbed they have to be to take remedial action—we simply try and quiet the noise, wherever possible and safe to do so. If we value our life-sustaining oceans, we should provide them with the same care and protection.

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Appendix

Quieting measures were categorized in four main areas:
1. Propeller noise reduction;
2. Machinery noise reduction;
3. Flow noise reduction; and
4. Other

Measures are reviewed in terms of:

- Advantages and benefits to the ship's design and operations;
- Disadvantages and challenges;
- Technology readiness;
- Cost impacts for implementation and operation;
- Applicability to different ship types;
- Effectiveness; in terms of frequency ranges and reduction in sound levels.

A final section of the table provides a summary of prediction methods for underwater radiated noise (Kendrick and Terweij 2019).

TERMINOLOGY

Advantages/Benefits

CC	-	Enhanced Crew/passenger Comfort
E	-	Reduced Emissions
F	-	Enhanced eFficiency
M	-	Reduced Maintenance
MA	-	Increased MAneuverability
S	-	Decreased Space Demand
W	-	Decrease in Weight

Disadvantages/Challenges

D	-	Increased Design effort
E	-	Increased Emissions
F	-	Reduced eFficiency
M	-	Increased Maintenance
MA	-	Reduction in MAneuverability
P	-	Increased complexity
S	-	Increased Space demand
W	-	Increased Weight

TRL - Technology Readiness Level

Cost Estimation

Range	-	Range of expected cost
Percentage	-	Percentage increase or decrease
Payback Period	-	Time in months/years to recover investment
Shorthand	-	Whether to expect an increase or decrease

Applicability

ReFit	-	RF
New Build	-	NB
Ship Type	-	By quadrant from Figure, except where indicated.

Effect

Frequency Range - Broadband/Narrowband; Expected Frequency Range Affected in Hertz (Hz)
Noise Reduction - Expected Noise Reduction in Decibels (dB):
Low (up to 5 dB),
Medium (5-10 dB),
High (greater than 10 dB

TECHNOLOGY MATRIX

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
1. **PROPELLER NOISE**							
1.1 PROPELLER/PROPULSOR DESIGN							
1.1.1 Reduction of Turns per Knot (TPK): Reducing the number of propellers turns per knot of speed, thus, reducing the speed of the flow at the tips of the blades. This requires a larger diameter of propeller and is applicable to both fixed and control pitched propellers. Reduces all forms of propeller cavitation (especially propeller tip cavitation) and increases Cavitation Inception Speed (CIS). [1]	**F** **CC**	**D**	**9**	**Unknown**	**NB** **1 - 4**	**ALL**	**Dependent on application – low to medium**
1.1.2 Increased Propeller Immersion: The hydrostatic pressure put forth on the propeller can affect the amount of cavitation that occurs and the CIS. The greater distance the propeller is from the free surface of the sea, the less cavitation will occur and the higher the CIS. Practical design constraints may limit. [2]		**D**	**9**	**Unknown**	**NB** **1 – 2**	**Unknown**	**Low**
1.1.3 High Skew Propeller: Propeller with blades swept back substantially more than conventional propellers. This allows for the blade to pass through the varying wake filed in a more gradual manner, improving the cavitation patterns. Load reduction on the tip of the propeller results in further reduction of propeller cavitation and increased Cavitation Inception Speed (CIS). [3] [4] [5]	**F** **CC** **M**	**D** **F** **W**	**9**	**10-15% Higher capital cost than conventional propellers**	**RF/ NB** **1 - 2**	**40-300**	**Medium, depending on initial wake field**
1.1.4 Contracted Loaded Tip Propellers (CLT): Propellers designed with an end plate allowing for maximum load at the propeller tip, which reduces propeller tip cavitation and increases CIS. The end plate also promotes a higher value of thrust per area (higher speed with smaller	**F** **CC**	**D**	**9**	**20% Higher capital cost than conventional propellers**	**RF/ NB** **1 – 4**	**40-300**	**Medium**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
optimum diameter) further reducing noise, vibrations and further increasing Cavitation Inception Speed (CIS). [5] [6] [7]							
1.1.5 Contra-rotating Propellers: Co-axial propellers, one propeller rotating clockwise & the other rotating counter clockwise. Increases CIS due to reduction in blade loading resulting in lower blade surface cavitation. Also, optimised flow circulation results in lower tip vortex cavitation. [8] [9]	**F**	**D** **M** **P**	**9**	**Much higher capital cost than conventional propellers**	**RF/ NB** **1 – 2**	**40-300**	**Low to medium**
1.1.6 Kappel Propellers: Propeller blades modified with tips curved towards the suction side. This reduces the strength of the tip vortex thus increasing efficiency, decreasing tip vortex cavitation, and increasing CIS. [10] [11]	**F**	**D**	**9**	**20% higher capital cost than conventional propellers [5]**	**RF/ NB** **1 – 2**	**40-300**	**Low**
1.1.7 Propeller with Backward Tip Raked Fin: Propeller modified in such a way the blades are curved towards the Pressure side (Opposite of Kappel Propellers), Studies have shown that there is an increase in efficiency and decrease in cavitation expected, however, there are few studies on the subject. [12]	**F**	**D**	**6** **9**	**Higher capital cost than conventional propellers**	**RF/ NB** **1 - 2**	**Unknown**	**Unknown** **(Improves wake flow)**
1.1.8 Podded Propulsors: This type of propulsion achieves improved wake performance to the propeller reducing cavitation and CIS. However, the drive configuration can increase medium to high frequency noise; see also 2.2.1 (Enabled by Diesel electric design) [13] [14]	**CC** **MA**	**D** **P** **F**	**9**	**Power dependent; typically 25% more than shafted system**	**NB** **1 – 4**	**Unknown**	**Low to Medium**
1.1.9 Water Jets: Operate in ducting internal to the ship, with increased pressures at the jet. Noise reduction from higher cavitation inception speed and by isolating the propeller from the sea. [14] [15] [16]	**F (high speed)** **high power density for fast, shallow draft vessels**	**F (at low speeds)** **M** **P** **W**	**9**	**Higher than conventional propeller and shafting; higher installation cost**	**NB** **2** **Highest speeds and some speciality types**	**All**	**High**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
1.1.10 Pump Jets: Combine a full pre-swirl stator, propeller and duct. Used in ultra-quiet applications such as submarines. [17]		**F** **M** **P** **W**	7 (for conventional ships)	**Higher cost than conventional prop**	**NB** **2**	**All**	**High**
1.1.11 Composite Propellers: Use of advanced composites to allow for blade (tip) distortion under load to delay cavitation onset and reduce blade vibration.	**CC** **W**	**D**	**6**	**Unknown at this time**	**NB/RF** **2, 3**	**All**	**Low**
1.2 WAKE FLOW MODIFICATION							
1.2.1 Pre-swirl Stator: Consists of Stator blades located on the stern boss in front of the propeller, flow is redirected before entering the propeller, increasing over all flow performance, thus reducing cavitation and increases CIS. [17]	**E** **F**	**D**	**9**	**Typical Payback Period: 24 months**	**RF/ NB** **4**	**All**	**Low**
1.2.2 Schneekluth Duct: An oval shaped duct located just forward of the upper half of the propeller, designed to improve the flow to the upper part of the propeller, this improves flow performance, lowering the formation of cavitation of propeller blade tips and increasing CIS. [18] [19]	**E-** **F**	**D**	**9**	**Typical Payback Period: 4 months**	**RF/NB** **1, 4**	**All**	**Low**
1.2.3 Propeller Boss Cap Fin (PBCF): Small fins attached to the hub of the propeller, reducing hub vortex cavitation, thus, reducing noise and vibration and increasing CIS. The design also recovers lost rotational energy, increasing efficiency. Similar concepts include ECO-CAP [19] [20]	**E** **F**	**D**	**9**	**Typical Payback Period:** **4 – 6 months** [21]	**RF/NB** **1, 4**	**≤ 1.0kHz**	**Medium**
1.2.4 Propeller Cap Turbines (PCT): Hydrofoil shaped blades integrated into the hub cap, similarly to PBCF reducing hub vortex cavitation, and increasing CIS. The design also recovers lost rotational energy, increasing efficiency. [19] [20]	**E** **F**	**D**	**9**	**Typical Payback Period:** **4 – 6 months** [22]	**RF/NB** **1, 2, 4**	**≤ 1.0kHz**	**Medium**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
1.2.5 Grothues Spoilers A small series of curved fins attached to the hull forward of the propeller, designed to improve flow to the propeller, reducing cavitation, increasing CIS and increasing fuel efficiency. [18]	**E** **F**	**D**	**9**	**Typical Payback period:** **Less than a year**	**RF/NB** **1, 4**	**Unknown**	**Low**
1.2.6 Mewis Duct A combination of a duct with pre-swirl stators integrated into the duct just forward of the propeller, thus having the benefits of both pre-swirl stators and grothues spoiler. Similar concepts include Super Stream Duct [5] [23]	**E** **F**	**D**	**9**	**Typical Payback Period:** **Less than a year**	**RF/NB** **1, 4**	**Unknown**	**Low**
1.2.7 Promas: Integration of the propeller, hubcap, rudder bulb, and rudder into one hydrodynamic efficient unit. Reduces propeller tip loading and limiting blade pressure pulses, thus, reducing cavitation and CIS. Similar concepts include Ultimate Rudder Bulb and SURF BULB[24]	**F** **E**	**D**	**9**	**Typical Payback Period: less than 2 years**	**NB** **1, 2**	**Unknown**	**Low to Medium (depending on initial flow)**
1.2.8 Costa Propulsion Bulb (CPB): Consists of two bulb halves that are welded to the rudder, in line with the propeller. Designed to recover energy losses aft of the propeller, by eliminating vortices caused by cavitation, ultimately reducing propeller vibrations and lowering URN. [25]	**F**	**D**	**9**	**Payback Period:** **4 – 15 years** **[22]**	**NB/ RF** **1, 2**	**Unknown**	**Low**
1.2.9 Twisted Rudder: Rudder designed to twist in order to vary the angle of attack to match water flow pattern. This reduces all cavitation and increases CIS. Used on a variety of vessels, including BC Ferries and U.S Navy Destroyers. [26]	**M** **F** **MA**	**D**	**9**	**Payback Period:** **4 – 15 years** **[22]**	**NB/ RF** **1, 2**	**Unknown**	**Low**
1.2.10 Asymmetric Body for Single Screw Vessels The purpose of designing an asymmetric after body is to account for the asymmetrical flow of a single screw propeller about the centerline. This will slightly increase CIS. [27] [3]	**F**	**D**	**9**	**Unknown**	**NB** **1, 4**	**Unknown**	**Low**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
1.2.11 CPP Combinator Optimization Adjusting pitch and rpm settings for controllable pitch propellers can mitigate the early onset of cavitation on pressure and suction sides both at constant speeds and during acceleration. This may also improve propeller efficiency in these conditions [77]	**F**	**D**	**8**	**Modest, requires software updates and potentially additional sensors**	**NB/RF** **All**	**All**	**Medium**
1.3 Supplementary Treatments							
1.3.1 Improved Manufacturing Processes: Tighter tolerances on blade manufacture may reduce cavitation. [28]	**F**	**D**	**9**	**10+% more expensive than standard propeller**	**NB/RF** **1 - 4**	**Unknown**	**Low**
1.3.2 Air Bubbler System (Prairie): Air injection through holes in the propeller blade tips, this fills the vacuum left by the cavitation as propellers rotate, allowing cavitation bubbles to contract more slowly as area that is under pressured is minimised. Reducing cavitation and increasing CIS. Must be used while docked as well to reduce marine growth clogging holes. Used by navies to reduce noise for stealth purposes. [29]		**D** **F** **M**	**6 (in commercial application)**	**20000 – 75000 +**	**NB** **1, 2**	**20 – 80** **500+**	**Medium**
1.3.3 Propeller Blade maintenance Imperfections of a propeller blade can encourage cavitation. Polishing between dry docks can prevent this, reducing cavitation and increasing CIS. [30]	**F**	**M**	**9**	**Unknown**	**RF** **1 - 4**	**All**	**Low**
1.3.4 Anti-Fouling Coating: A coating applied to the surface of a propeller with the purpose of reducing propeller fouling. Research has been done regarding underwater noise with varying results. [31]	**M**		**9**	**Payback Period:** **2 years** **[22]**	**NB/RF** **All**	**50 -10000Hz**	**Low**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
1.3.5 Application of Anti-Singing Edge: Modification to the propellers trailing edge, designed to alter naturally occurring vortex shedding phenomenon. [32] [33]			9	**Increase in manufacture cost**	**NB/RF** **1 - 4**	**10 – 12000**	**High (where singing is a problem)**
2.0 MACHINERY							
2.1 Machinery Selection							
2.1.1 Prime Mover Selection The choice of prime mover (main engines) has a strong influence on the basic machinery noise characteristics of the ship and on the potential use of mitigation measures. Diesels are currently the default choice of prime mover for almost all commercial vessels and so are assumed here except where otherwise indicated. See main report for additional discussion.							
2.1.2 (Diesel) Electric: Using electric rather than mechanical transmission enables and/or facilitates many noise reduction approaches, from the use of mounts and enclosures to active noise cancellation. A wider range of propulsor selections are also available. Electrical transmission has worse efficiency than mechanical, and capital costs are higher so use is generally in vessels where other benefits outweigh these costs. [34]	**MA (paired with azimuth thrusters)** **S** **W**	**F**	9	**Highly variable**	**NB** **Most applicable to vessels that have widely varying speeds in operational profile, and/or redundancy requirements for dynamic positioning, etc**	**ALL**	**High**
2.1.3 Gas/Steam Turbine Rotating turbines are generally quieter than diesels but have lower fuel efficiency and higher capital cost. Very few steam ships are now constructed (other than for nuclear vessels) but many naval vessels use gas turbines for high power density. [35]	**S** **CC** **E (compared to Diesel)**	**F** **D** **M** **P**	9	**Much higher capital cost than diesel**	**NB** **1, 2**	**ALL**	**High**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
2.1.4 Stirling Engine: The external combustion stirling engine produces lower noise then conventional internal combustion engines. Load following characteristics are relatively poor, so difficult to have rapid variations of power. Main uses are for submarines and naval vessels to reduce radiated noise. [36]	**F** **E** **(multiple fuel capability)** **M**	**W** **S**	**6**	**High capital cost**	**NB**	**Unknown**	**Medium**
2.1.5 Azimuthing Propulsors Azimuthing propulsors may have motors inside the hull with transmission gears (electro-mechanical) or outside the hull in a propeller fairing (fully electric). Either type can have propulsor noise benefits as noted in 1.1.8. Electro-mechanical types may have gear noise to mitigate while fully electric have electric motor noise. Limited public domain information is available on the machinery noise characteristics of either type though both claim excellent performance. [13] [14]	**F** **(compared to conventional diesel electric)** **MA** **W** **CC**	**F (compared to conventional diesel)**	**9**	**Power dependent; typically 25% more than shafted system**	**NB** **1, 2, 3**	**Unknown**	**Unknown**
2.2 Machinery Treatments							
2.2.1 Resilient Mounts (Equipment): Spring mounts impede the transmission of vibration energy from machinery, and the generation of energy into the water from the hull. Requires appropriate selection and installation of mounts. Not generally practical for heavy 2-speed diesels. [37]	**CC**	**S** **W**	**9**	**20 – 2000$ per mount; large engines require many mounts and installation cost,**	**NB/ RF** **2, 3**	**All**	**High, best at higher frequencies**
2.2.2 Floating Floor (Deck): A Floating/False deck is constructed and resiliently mounted to the deck, effectively isolating all machinery on the false deck; applicable to lighter equipment only. [37]	**CC**	**S** **W**	**9**	**Unknown**	**NB/ RF** **All**	**All**	**Low, main benefits internal**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
2.2.3 Raft Foundation (Double stage vibration isolation system) One or several pieces of machinery are mounted on an upper layer of mounts supported by a raft (steel structure) which is further supported on the hull girder on a lower level set of mounts. This reduces noise by creating an extra impedance barrier to the transmission of vibration energy. Often used for engine/gearbox or engine/generator; not applicable to 2-stroke diesels due to high weight. [38]	**CC**	**W** **D** **S**	**9**	**Adds significantly to installation cost; can be 10%+ of cost of installed equipment**	**NB/ RF** **2, 3**	**All**	**High, best at higher frequencies**
2.2.4 Acoustic Enclosures: Structures designed to enclose a specific piece of machinery, absorbing airborne noise. This reduces the airborne transmission of energy to the hull and the generation of URN from the hull. [39]. Typically used only with smaller diesels and gas turbines.	**CC**	**S** **D**	**9**	**Adds significantly to installation cost; can be 10%+ of cost of installed equipment**	**RF/ NB** **2, 3** **Used on vessels requiring very low noise signatures such as warships, research vessels after treatment of other noise paths.**	**125 – 500**	**High**
2.2.5 Active Cancellation: Reduction of machinery excitation of the hull structure by means of secondary excitation to cancel the original excitation. Uses sensors for measuring excitation, a device to read the sensor and actuators to produce counter phase excitation. Capital cost is high. [40]	**CC**	**S** **D**	**6**	**Highly variable**	**NB**	**Effective at tuned frequencies**	**High** **Effective for discrete frequencies rather than overall noise levels**
2.2.6 Spur/Helical Gear Noise Reduction Gear design can be used to optimize number of teeth & profile shift angle. This will optimize sound reduction due to teeth mashing lowering machinery noise. Also requires high quality manufacturing [41] [42]	**F** **M**	**D**	**9**	**Increase in manufacture cost, can double gear cost (milspec)**	**NB**	**Effective mainly at gear meshing frequencies**	**Medium/ High**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
2.2.7 Control of Flow Exhaust gases (Enabled by 2-stroke diesel Engine) Exhaust flow component designed to reduce noise produced by sudden gas expansion during the combustion/exhaust stroke of a 2-stroke diesel engine. [43]	**F**	**D**	**3**	**Unknown**	**NB** **1, 4**	**Unknown**	**Low**
2.2.8 Metallic Foam A porous material designed to be used in the tanks of diesel or water ballast tanks, to reduce underwater radiated noise. The material has open enhanced acoustical properties when saturated by liquids [44]	**CC**	N/A	**6**	**Unknown**	**Unknown**	**Unknown**	**Unknown, claimed as High**
2.2.9 Structural (Hull/Girder/Floor Thickening) The thickness of structural members are directly linked to URN mitigation. Rigid structure creates impedance mismatch and is particularly effective used with resilient mounts; added weight is also useful for noise transmission reduction [45]	**CC**	**D** **S** **W** **F**	**9**	**Unknown**	**NB** **2, 3**	**10 – 1000**	**Medium**
2.2.10 Structural Damping Tiles The application of dampening tiles integrated into the structure of a vessel, absorbing vibration energy, resulting in a reduction of URN. [45]	**CC**	**W** **D**	**9**	**$50 – 150 per m^2**	**NB/RF** **2, 3**	**200+**	**High if treatment is extensive, best at higher frequencies**
2.2.11 Acoustic Decoupling Coating Layer of rubber foam or polyethylene foam applied to the exterior of the vessels hull, designed to decrease noise radiation from machinery vibration energy. (most commonly applied to submarines) [46]	**F**	**M** **(Hard to control corrosion between tiles & hull)**	**7**	**$250 – $1000 per m^2 plus engineering design and installation costs**	**NB/RF** **2, 3**	**800+** **100 – 800**	**Unknown, claimed as High forhigher frequencies**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
2.3 Alternative fuel selection							
2.3.1 Fuel Cell Produces electricity through chemical reaction, this is done by converting hydrogen and oxygen to water. Significantly quieter than any combustion engine. (The efficiency of fuel cells themselves are quite high however, when infrastructure & storage is taken into account compared to diesel or other methods, the efficiency decreases significantly) [47] [48] [49]	**CC** **E** **W** **F**	**D** **P** **S**	**7**	**High capital cost** **Increase in fuel cost**	**NB**	**All**	**High**
2.3.2 Battery (Stored electrical energy, also supercapacitors) Draws on stored energy provided by shore power or from integrated electric power plant on ship. Batteries themselves are inherently silent removing all prime mover noise when in use. Low energy density means can only be used for short voyages, or for portions of longer voyages in (e.g.) noise-sensitive areas. [50]	**E** **F**	**S** **W**	**9**	**High capital cost**	**NB/RF** **2, 3** **Applicable to vessels with short routes or highly varying speed profiles**	**All**	**High**
3.0 Hydrodynamic							
3.1 Hull Treatments							
3.1.1 Underwater Hull Surface Maintenance Poor hull surface maintenance can lead to resistance increases. This can cause the machinery load on machinery to increase and propeller RPM to travel at the same speeds, thus increasing URN. Hull surface maintenance must be completed regularly to avoid this. [51]	**F** **E**	**M**	**9**	**Hull polishing cost depends on ship size**	**RF** **All**	**All**	**Low**
3.1.2 Air Bubbler System (Masker): Air injection around the hull of the vessel to reduce noise created by machinery, creates a blanket of air bubbles	**F**	**M**	**7 (in comme**	**20000 – 75000 +**	**NB**	**20-80**	**High [78]**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
between the machinery noise and water, and uses tubing systems and an air compressor. Also has the effect of highly reducing marine growth on the hull, improving overall efficiency. Must be used while docked as well to reduce marine growth clogging tubing holes. Used by navies to reduce noise for detection stealth purposes. [29]		**D**	rcial ships)	**Payback Period:** **4 – 15 years** [22]	**1, 2, 3**	**500+**	
3.1.3 Hull Air Lubrication: Air lubrication systems (ALS) have been introduced by several shipbuilders to reduce skin friction resistance for power savings [80], [83]. It is probable that this will have similar effects to Masker systems on naval vessels.	**F**	**D** **M**	**8**	**Similar to 3.1.2**	**NB** **1, 2**		**High**
3.2 Hull Appendage/Design							
3.2.1 Efficient Hull Forms Hydrodynamically efficient hull forms will reduce power requirements and therefore both machinery and propulsor noise. Such hulls will also generally have good wake characteristics, increasing cavitation inception speeds. [52]	**F**	**D**	**9**	**Unknown**	**NB** **All**	**ALL**	**Application dependent**
3.2.2 Stern Flap/Wedge Small extensions from the lower transom. Modifies the stern wave produced by the vessel and reduces powering requirements, reducing hydrodynamic noise. Similar benefits will come from other stern flow modification appendages, such as hull vanes and interceptors. [53] [54]	**F** **E**	**D**	**9**	**Unknown**	**NB/ RF** **1, 2**	**ALL**	**Low**
4.0 Other Mitigation Technologies							
4.1 Wind							
4.1.1 Kite Sails Kites attached to the bow of a Merchant/commercial vessel, designed to create thrust that replaces power from conventional machinery and propeller thrust. [56]	**F** **E**	**D**	**8**	**Payback Period:** 15+years [22]	**NB/ RF** **1, 4** **Not suited to smaller vessels**	**ALL**	**Medium to High** **(Depending on speed reduction and primary**

Treatment/Description	Advantages/ Benefits	Disadvantages/ Challenges	TRL	Cost Estimation Percentage/ Range	Applicability RF/ NB Ship Types	Effect Frequency Range (Hz)	Effect Noise Reduction (dB)
					or to operations on short routes and fixed schedules, e.g. smaller ferries		**propulsion source)**
4.1.2 Flettner/Magnus Rotors Tall, smooth, rotating cylinders with an end plate at the top. Extruding from the main deck of the vessel. An external force with wind causes rotation creating thrust that replaces power from conventional machinery and propeller thrust. Similar to conventional sails in URN reduction. [57]	**F**	**D** **S** **P**	**8**	**Payback Period:** 15+years [22]	**NB/ RF** **1, 4** **Not suited to smaller vessels or to operations on short routes and fixed schedules, e.g. smaller ferries**	**ALL**	**Medium to High** **(Depending on speed reduction and primary propulsion source)**
4.1.3 Conventional Sails As with kites and rotors, any form of sail assist can reduce machinery power requirements and propeller noise.	**F**	**D** **S** **P**	**9**	**Dependent on vessel and installation**	**NB** **3, 4** **Not suited to operations on short routes and fixed schedules, e.g. smaller ferries**	**ALL**	**Medium to High** **(Depending on speed reduction and primary propulsion source)**
4.1.4 Cold Ironing (Shore Power) Provision of higher power shore supplies to large vessels (cruise ships, containers ships) can allow these vessels to turn off all generating equipment while in port, lowering URN while alongside. [81]	**E** **F** **M**	**S** **W**	**9**	**$1.5 m per berth, $400k per vessel**	**NB/RF** **1** **Also often used for smaller vessels with standard home ports**	**<1000**	**Medium**

Predicting URN				
Prediction Method	**Description**	**Comments**	**Software/Vendors (examples)**	**TRL**
1.0 Computational				
1.1 Propeller				
Empirical; e.g. Tip Vortex Cavitation Method	An approximate method based on numerical and experimental data. It is generally considered that tip cavitation produces the predominant noise produced by cavitation followed by sheet cavitation. [58], [84]	Semi-empirical methods require detailed knowledge on the appropriate empirical input parameters to be used which need to be scaled to the results of model or full scale tests. Uncertainty levels can be high.	Used by DNV and others for noise prediction	**9**
Semi-empirical, e.g. Lifting Surface method\potential flow	Propeller Blades are analyzed as lifting surfaces over which singularities such as the vortex are distributed over the surface to model the effects of blade loading/thickness. [65] [66] [67]. To perform this method detailed propeller geometry & wake distribution must be provided, pressure distribution calculations must be performed to produce lifting surfaces from the blade geometry. From here determination of sheet cavitation regions can take place, than calculations of sheet cavitation swept area can occur. This can then be converted to broad band noise levels using a conversion equation such a Brown's Formula [68], [88]	Incompressible flow methods such as lifting surface cannot capture viscous flow features such as boundary layers and vortices and have difficulty in modelling cavitation accurately.	PUF PROPCAV PROCAL	**8**
Computational Fluid Dynamics	Tip Vortex cavitation can be predicted in many different ways using CFD. [58] The Reynolds stress turbulence model may be used for computation of propeller flow using FLUENT [59], transition-sensitive eddy-viscosity turbulence model to resolve the boundary transition layer effects [60], Commercial Reynolds Averaged Navier Stokes (RANS) solvers [61] [62], RANS solvers need to be paired with other methods to change the form of data calculated for example Detached-Eddy Simulations (DES) paired with the Spalart-Allmaras eddy viscosity model [63] or Direct Navier-Stokes simulations [64]. Conversion of tip vortex intensity into URN levels for high frequencies in particular requires similar approached to Lifting Surface methods using Brown's Formula or others as direct capture of tip vortex cavitation is difficult [89]	RANS codes consider viscous flow features in a more simplified way than LES (large eddy simulation) codes, giving lower accuracy in some cases but with less computational effort. None of these methods can be used other than by highly specialized personnel.	OpenFoam (Simple Foam RANS Solver) ANSYS (FLUENT) Star CCM+ ANSYS CFX ReFRESCO	**7**
1.2 Machinery				
Empirical [69]	Empirical formulae have been derived for many airborne, duct-borne and structure-borne noise transmission paths, and can be combined into overall prediction methodologies.	These methodologies are mainly concerned with internal noise and require manipulation to be used for URN prediction.	DNVGL in-house software CABINS software from TNO	**9**

Predicting URN				
Prediction Method	**Description**	**Comments**	**Software/Vendors (examples)**	**TRL**
Semi-empirical: Statistical Energy Analysis (SEA) **[70]** **[71]**	SEA uses energy flow relationships to calculate the diffusion of acoustic and vibration energy through a structure before its propagation into the water. In the SEA method, a complex structure is considered as a system formed of coupled subsystems. Each subsystem represents a group of modes with similar characteristics and a storage of energy. SEA predicts the average response of the structure, reducing the amount of calculation required.	SEA methods are still reliant on empirical data for calibration, and the accuracy of predictions can be less than for empirical. Only specialized personnel can use method reliably.	Designer-NOISE (Noise Control Engineering) SEAM (Cambridge Collaborative) Deltamarine	**8**
Full Frequency Range Vibro-Acoustic Prediction	Utilizes statistical energy analysis (SEA), structural and acoustic finite element (FE), and boundary element (BE) solvers alone and combined in hybrid models for vibroacoustic response to machinery, flow-related and hydroacoustic inputs. FE and BE are used for low frequency ship response and URN prediction, hybrid FE/BE/SEA for higher frequency predictions, and SEA for high frequency predictions. Measured and empirical information can be incorporated as user-defined properties/characteristics.	The advanced SEA algorithms in these methods do not rely on empirical data. Considerable expertise in structural-acoustics is required to use these methods	VAOne (ESI Group) Wave6 (Dassault Systemes)	
Low Frequency Noise Prediction/Finite Element Methods **[72]**	The purpose of this method is to calculate URN caused by machinery noise similarly to the SEA method. The method requires a 3D CAD model converted to a Finite Element model. Various loads and analyses can take place to acquire results for radiated noise analysis. From here a wetted surface FE model and a Boundary Element (BE) code can be coupled to predict low Frequency URN		FE Software (similar to Ansys) Boundary element based code (Ex: AVAST)	**8**
1.3 Entirety				
Noise propagation modeling **[85], [86], [87]**	- Various models can be accessed from the websites listed in the references using methods including parabolic equation, ray trace, normal modes and spectral integration. Some commercial codes have also been developed.	All methods can only be exercised by specialized personnel.	RAM KRAKEN OASES dBSea [73]	**9**
2.0 Model Scale				
Propeller cavitation tunnel	Cavitation tunnels model the propeller and in some cases the hull form immediately ahead of the propeller, reducing the pressure in the tunnel in accordance with scaling laws. Results predict cavitation inception speeds and the development of cavitation patterns. Tunnel tests can also be used to predict pressure pulses & cavitation noise.	Model scale cavitation testing has challenges for replication of wake field, blockage effects and others. Noise measurements are influenced by reverberation from tank walls, background noise and uncertain scaling laws. Open literature available regarding radiated noise full scale and	Approximately 20 commercial model testing facilities have cavitation tunnels. Large scale tunnels are preferable to	**9**

Predicting URN				
Prediction Method	**Description**	**Comments**	**Software/Vendors (examples)**	**TRL**
	Noise levels from the model propeller are extrapolated to full scale using a variety of scaling rules. [78], [79]	model scale comparison and extrapolation can be found in [76].	reduce scaling uncertainties. [74]	
Ship cavitation tank	Cavitation tanks extend the tunnel modelling approach by using whole ship models in a depressurized chamber. This allows for the creation of more accurate wake fields and flow patterns both upstream and downstream of the propeller, giving a more accurate prediction of cavitation. [76], [77]	While some modelling issues are improved compared to cavitation tunnel others become more challenging.	Only two depressurized tanks are in operation, in China and the Netherlands [75]	**9**