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Underwater noise abatement: Economic factors and policy options

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ABSTRACT

Underwater noise pollution is becoming globally recognised as a significant threat to aquatic ecosystems and the resources they provide. The effects of noise pollution extend from blue whales to zooplankton, impacting threatened species and affecting key industries including fisheries and ecotourism. In response, policymakers in some jurisdictions have made substantive high-level commitments to address noise pollution, however the implementation of noise reduction measures (noise abatement) remains limited. To support the development of effective noise management policies, this paper explores the economic and policy context to noise abatement in three major noise-generating industries: shipping, offshore windfarm construction, and seismic surveying for oil and gas. In each case, tractable policy options are identified which make considered use of command-and-control and incentive-based measures in light of the available noise abatement methods. Drawing on instructive examples from terrestrial noise management and other sectors, it is concluded that such measures offer the most promising long-term solution to deliver existing and future policy commitments to manage cumulative levels of underwater noise pollution.

1. Introduction

Mounting scientific evidence links noise exposure to a range of detrimental effects on marine mammals, sea turtles, fish, and invertebrates (Williams et al., 2015). These effects extend from blue whales (Di Iorio and Clark, 2010) to zooplankton (McCauley et al., 2017), and include species which are critically endangered (Parks et al., 2007), commercially important (Engås et al., 1996), and which mediate ecosystem properties (Solan et al., 2016). As a result, underwater noise pollution is now firmly on the policy agenda at both national (Hatch et al., 2016; Merchant et al., 2016) and international (e.g. European Commission, 2008; IMO, 2014; OSPAR, 2017; UN, 2018) levels.

While the risks to marine ecosystems are clear, quantifying the ecological cost of noise pollution remains challenging. Effects on individual animals across a wide range of species point toward the risk of impact at the population and ecosystem scales (Tyack, 2008; Slabbekoorn et al., 2010). However, quantifying the link between noise exposure and large-scale effects is complex due to the many other factors which influence populations and ecosystems, and gathering direct evidence of large-scale effects is not expected to be possible in the near term.

This uncertainty over the ecological cost of noise pollution presents a dilemma for decision makers: how to quantify the environmental benefit of quieting the oceans when weighed against the economic cost of implementing quieting measures. Without an economic valuation of the resulting benefits to ecosystem services (e.g. fisheries, wildlife tourism) and/or a quantification of benefits to biodiversity, the utility of cost-benefit analysis and similar decision-support tools breaks down.

In theory, this scientific uncertainty should compel the policy process to adopt the precautionary principle. This is a requirement, for example, of signatories to the Rio Convention on Biodiversity Conservation, the OSPAR Convention, and Member States of the European Union. These conventions all assert that precaution should be exercised under conditions of scientific uncertainty. Some also go further to stipulate that pollution should be abated at source, and that the polluter should pay (polluter pays principle, e.g. European Union, 2010). Despite these agreements and high levels of public concern over marine pollution (Lotze et al., 2018), precautionary management measures to reduce noise pollution remain scarce.

To develop the policy debate further, this paper focuses on the challenge of designing effective noise abatement policies. By elaborating the cost side of the cost-benefit equation, policymakers can be more informed of the measures available to them, and the ways in which these can be introduced to avoid unnecessary disruption to important sectors. Three major noise-generating industries are taken as case studies: commercial shipping, pile driving for offshore wind farms, and seismic surveying for the oil and gas industry. Based on the unique policy and economic contexts of each case and the availability of suitable noise abatement methods, policy options for implementing noise abatement are identified.

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2. Mitigation measures and abatement at source

While noise abatement measures are comparatively rare, other forms of noise mitigation are sometimes applied. However, these mitigation measures do not typically reduce the amount of noise pollution entering the marine environment. These interventions include:

- **Spatiotemporal restrictions** on noise-generating activities, either in the planning stage (e.g. restricting activity in or near fish spawning grounds during the spawning season), or in real time during the activity based on short-range detection of marine mammals (e.g. temporarily halting a seismic survey if a marine mammal is detected within a specified exclusion radius; JNCC, 2017);
- **Introduction of additional noise** of lesser intensity with the intention of dispersing animals before more harmful noise levels are emitted, e.g. use of acoustic deterrent devices (ADDs) prior to activities, and ramp up of pile driving hammer energy or seismic survey source level (JNCC, 2017).

These mitigation measures may reduce acute impacts on particular (protected) species or taxonomic groups (Wright and Cosentino, 2015), and should be used if appropriate. However, they do not address effects on other taxa, nor the cumulative and long-term effects of repeated low-level noise exposure from multiple sources. Furthermore, since many of these measures rely on in situ observations or accurate animal distribution data, preventative action can only be effective if this evidence is sufficient and up-to-date (Faulkner et al., 2018). Sightings and acoustic detections of animals are contingent on weather conditions, surfacing behaviour, and observer bias; animal distribution data is often sparse or outdated.

The only certain way to lower the risk of impact is *noise abatement* – reducing the amount of noise pollution entering the marine environment. This can be achieved by reducing noise emitted at source, and by reducing the amount of noise-generating activity.

3. Policy approaches to noise abatement

The question to be addressed is then *how best to design noise abatement measures*. Broadly speaking, policy measures to manage environmental pollution can be categorised as *command-and-control* (CAC) approaches or *incentive-based measures* (IBMs), also known as *market-based measures* (MBMs; Perman et al., 2011; Fig. 1).

CAC approaches apply mandatory controls to industrial activity, either through prescribed abatement technologies, limits on pollution levels per activity, or limits on the amount of activity (Fig. 1). While such approaches provide a high degree of control to regulators and have been effective in many cases (Cole and Grossman, 1999), specifying suitable abatement targets and monitoring compliance can in some cases be burdensome for regulators. It is also difficult for regulators to ascertain the compliance costs to industry a priori, meaning that opportunities for more efficient and effective measures may be missed.

IBMs, by contrast, offer some flexibility to industry, either through a 'cap-and-trade' system, in which transferable pollution permits are traded among polluters (affording control over cumulative pollution levels via the total number of permits), or through economic incentives, which encourage pollution reduction through subsidies or taxes linked to emissions. This flexibility allows abatement effort to be focussed where it is least costly, and can incentivise industry to develop improved noise abatement methods. However, to be effective, taxes and subsidies must provide sufficient economic incentive to influence industry behaviour, and the applicability of IBMs in general must be considered carefully for the specific environmental context. For example, since the impact of noise pollution depends on the location and timing of emissions (i.e. noise is not a universally mixing pollutant like CO_2), the use of a 'cap-and-trade' system will generally be unsuitable without bespoke adaptations, since permits having equal value would not reflect the differing levels of risk due to location and timing.

The most appropriate and effective policy option will vary according to industry-specific considerations, including the nature of available noise abatement methods. Depending on these factors, the most effective interventions may be either command-and-control or incentive-based measures, and may target the type of technology used (technology measures), the noise output per activity (operational measures), or the amount of noise-generating activity (activity reduction measures; Fig. 1).

Fig. 1 also illustrates how noise abatement fits into higher-level management of noise pollution. Spatiotemporal restrictions do not achieve noise abatement (Section 2), but may reduce risk of impact for target species (selective impact mitigation). Cumulative levels of pollution can be managed through target setting (Fig. 1) – agreeing an overall 'noise budget' at an appropriate management level (Merchant et al., 2018) – and implementing this via cap-and-trade (if appropriate) or by cascading noise targets to regulatory decision-makers.

In the following sections, factors affecting noise abatement policy

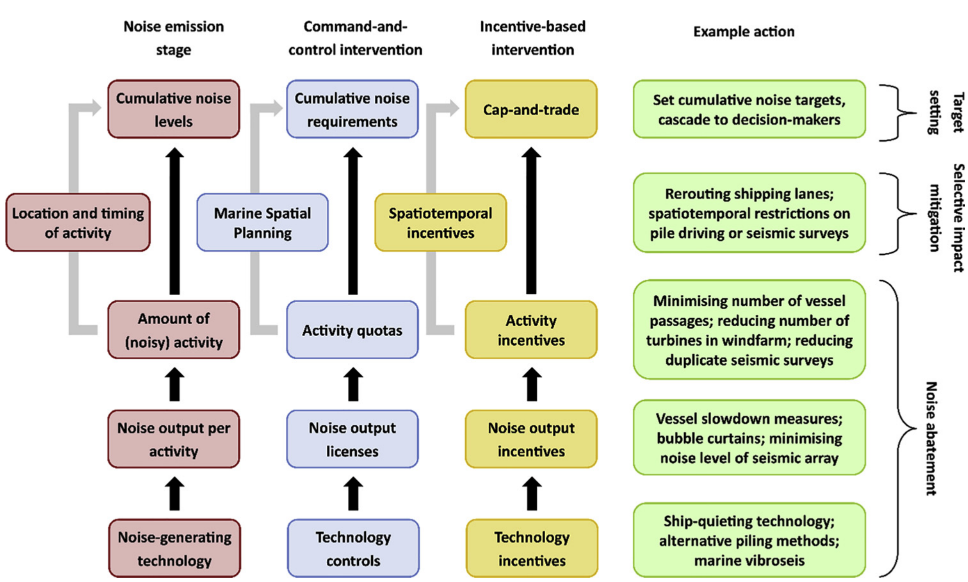

Fig. 1. Stages of noise emission, corresponding command-and-control and incentive-based interventions, and examples of actions for each stage. Adapted from Perman et al. (2011).

options are examined for three major noise-generating sectors: shipping, offshore wind farm construction, and seismic surveying for oil and gas.

4. Shipping

4.1. Context

At a global scale, shipping is the most widespread and persistent source of underwater noise. As the primary vehicle of global trade (~80% by volume; UNCTAD, 2017), shipping – and its resulting noise pollution – is closely linked to global economic activity. Between 1963–1965 and 1994–2001, noise levels in the Northeast Pacific rose by up to 10 dB at low frequencies (< 300 Hz) due to shipping (Andrew et al., 2002), an increase which was correlated with the rise in world Gross Domestic Product (Frisk, 2012). Based on shipping growth over the last decade, projected growth in large vessel traffic would substantially heighten levels of shipping noise pollution in the coming decade (Kaplan and Solomon, 2016).

The pervasive nature of shipping noise pollution has raised concern that it is causing widespread behavioural and physiological effects with consequences at the population level (Tyack, 2008; Slabbekoorn et al., 2010). Exposure to ship noise pollution can elicit behavioural responses and increase physiological stress in fish (e.g. Wysocki et al., 2006) and cetaceans (Rolland et al., 2012), and appears to mask acoustic communication (Parks et al., 2007). In Arctic regions where sea ice retreat is opening up new shipping routes, the acoustic habitat is being degraded both by increased anthropogenic noise and by the human-induced loss of sea ice coverage, since this exposes subsea habitats to more weather-driven noise (Roth et al., 2012).

From a policy perspective, implementing ship noise abatement measures presents significant challenges. Unilateral regulatory interventions could place an economic burden on trade, potentially leading to competitive disadvantage. An internationally coordinated approach is therefore likely to be favoured. The International Maritime Organization (IMO), a UN agency which sets global requirements for international shipping, has already issued non-mandatory guidance on ship-quieting measures (IMO, 2014). Additional measures at regional scale (e.g. EU, OSPAR) could complement and provide impetus to the policy process at UN level.

4.2. Noise abatement options

4.2.1. Technological measures

The most significant source of underwater noise from vessels is propeller cavitation (IMO, 2014). Above the cavitation inception speed, the rotating propeller generates oscillations in water pressure large enough to cause bubbles of water vapour to form, which release broadband noise when they subsequently collapse. Cavitation can be reduced by modifying the propeller and/or hull, and by injecting air through the propeller blades. Underwater noise is also generated by onboard machinery (e.g. engine, generators): noise transmission through the hull can be reduced by vibrationally isolating machinery and optimising its placement in the hull (IMO, 2014).

Implementing these ship-quieting technologies at the design stage (rather than retrofitting) significantly reduces the cost (Spence and Fischer, 2017). Retro-fitted design modifications to improve energy efficiency may also lead to lower noise levels (Gassmann et al., 2017), although the most energy efficient design may not necessarily be the quietest.

4.2.2. Operational measures

Ship speed can affect ship noise emissions (McKenna et al., 2013), although for some vessels the relationship may be weak or non-existent, particularly for vessels with controllable pitch propellers (IMO, 2014). Despite this caveat, it appears that overall, ship speed restrictions can reduce noise levels: this was demonstrated in a vessel slowdown trial in Haro Strait, Canada in 2017 (Trounce, 2018). However, slower vessels take longer to transit, leading to a trade-off between the duration and the intensity of noise exposure (McKenna et al., 2013) which may have varying effects on different marine species. One study indicated that the optimal trade-off between duration and intensity may be achieved at around 8 knots (McKenna et al., 2013).

Underwater noise can be exacerbated by poor vessel maintenance: marine fouling on the propeller can increase cavitation, nicks on the propeller can cause loud tones, and surface roughness on the hull increases drag, heightening load on the propeller which can also increase noise (IMO, 2014). Regular maintenance of the propeller and hull may therefore achieve modest reductions in noise.

Finally, requiring or incentivising vessels to travel in convoy may reduce cumulative noise levels compared to vessels transiting ad hoc, since quieter vessels within the convoy will be ‘cloaked’ by their noisier companions (Heise et al., 2017).

4.2.3. Activity reduction measures

Policies incentivising the use of fewer, larger vessels for shipping could lead to cumulative noise reductions. Although larger vessels tend to generate more noise (McKenna et al., 2013), their greater carrying capacity may offset their higher noise output by slowing growth in overall numbers of large vessels. Policies scaled to vessel capacity rather than on a per-vessel basis could therefore incentivise the use of fewer vessels and lead to reduced noise levels (see next section).

4.3. Policy options

As the measures in Section 4.2 demonstrate, the greatest potential for shipping noise abatement is via ship-quieting technologies, with relatively limited scope for substantial abatement via operational and activity reduction measures. Retrofitting quieting technologies to existing vessels is more costly and less effective than quieting at the design stage (Spence and Fischer, 2017). However, requirements or incentives for new vessels may be slow to yield results, due to the long operational lifetimes of extant vessels (~20 years on average for large vessels; UNCTAD, 2017). Another approach is to target the noisiest existing vessels (Leaper and Renilson, 2012): field measurements of individual vessels suggest this could efficiently reduce the cumulative noise output of the global fleet (Viers et al., 2017). The most effective option may therefore be to combine requirements for new vessels with measures that target the noisiest existing vessels (Fig. 2).

4.3.1. New vessels

Quieting vessels at the design stage could be achieved via economic incentives or mandated standards (see Section 3 and Fig. 1). Mandatory standards based on the noise output of individual vessels are the most direct option. This has been the approach taken in the aviation industry,

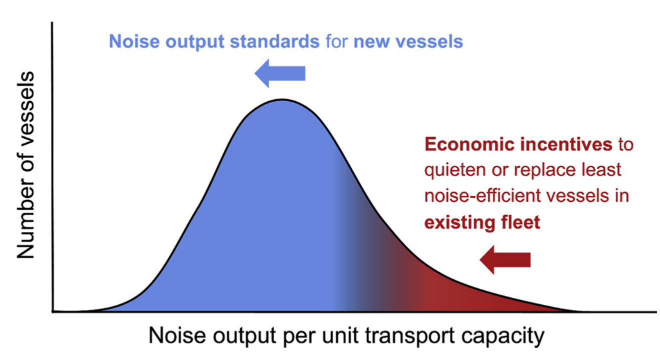

Fig. 2. Proposed approach to ship noise abatement combining economic incentives for the noisiest existing vessels with mandatory noise output standards for new vessels.

for which the International Civil Aviation Organisation (ICAO) has set aircraft noise standards since 1973 (Smith, 2004). Recognising that heavier aircraft have greater transport capacity, the ICAO standards are scaled according to Maximum Take-off Mass (MTOM), allowing heavier aircraft to be noisier. A similar approach could be taken for shipping noise, with noise requirements scaled to vessel transport capacity (Fig. 2), reducing noise emissions of new vessels and incentivising the use of fewer, larger vessels. A phased approach to implementation could reduce disruption to industry, e.g. by beginning with the largest vessels, similarly to ICAO requirements (Smith, 2004).

4.3.2. Existing vessels

The first challenge in regulating the existing fleet is to determine the noise output of operating vessels. An international standard exists for measuring ship noise emissions (ISO, 2016). However, this does not specify the operating condition of the vessel. Since noise output will vary with ship speed and other operational factors (McKenna et al., 2013), measurements should be made under realistic conditions, i.e. while transiting at typical cruising speed. This implies monitoring along shipping routes rather than around ports, and could be efficiently implemented in high-density shipping routes (e.g. Straits of Dover, Gibraltar, Hormuz, Malacca). Since such monitoring would serve large regional areas, this could be resourced through international bodies such as Regional Seas Conventions (e.g. OSPAR, Cartagena Convention) which coordinate marine policy in their respective regions. Registries of vessel noise output could then be compiled at global or regional level. Once monitoring has become embedded and ship noise registries established, incentive-based measures targeting the most polluting vessels can be implemented. In the meantime, port-based schemes such as the Port of Vancouver's ECHO programme may offer some incentive to ship owners to have their vessels assessed for noise output: this scheme offers reduced port fees for vessels which meet certain ship noise certifications (e.g. those issued by Bureau Veritas, DNV GL, RINA). However, with many ports competing for business, ports have clear disincentives against adopting more assertive measures without larger-scale coordination.

5. Pile driving for offshore wind farms

5.1. Context

Power generation from offshore wind is rapidly increasing in many countries, with some analysts projecting the sector to expand sixfold globally by 2030 (BNEF, 2017). This growth has been driven by renewable energy targets (e.g. 20% of final energy consumption by 2020 in EU; European Commission, 2009) designed to reduce CO_2 emissions. While the benefits of offshore wind for decarbonising the energy sector are clear, the risk of impact to marine life, including via noise pollution during construction, has raised considerable concern. Offshore wind turbines can be supported by various structures (e.g. floating bases, gravity bases), but the most common are piled foundations – single (monopile) or multiple (jacket or tripod designs) steel cylinders, usually driven into the seabed using a percussive piling hammer. This method involves repeatedly striking the pile (typically several thousand times) with an energy of up to several thousand kilojoules, generating high amplitude pulses of underwater noise. Once installed, however, the noise output of operating windfarms is low, with individual turbines emitting ∼126 dB re 1 μPa at 50 m (Pangerc et al., 2016). Offshore windfarms therefore present a more temporary source of significant noise pollution than shipping or seismic surveys,

The effects of pile driving noise observed in situ include displacement of harbour porpoise by up to ∼25 km (Dähne et al., 2013) and physiological stress in juvenile seabass (Debusschere et al., 2016). Controlled exposure studies indicate that physical injury and auditory impairment can also occur near to the piling operation (Casper et al., 2013).

Regulatory responses to offshore windfarm construction noise have differed. In Germany and several other western European countries (e.g. the Netherlands, Denmark), regulations are routinely applied which constitute a de facto requirement to use noise abatement measures such as bubble curtains (see below). In other countries, noise abatement has not yet been implemented, including in two of the top three offshore wind energy producers by wattage – the UK (1st) and China (3rd); Germany is 2nd (as of 2017; GWEC, 2018).

5.2. Abatement options

5.2.1. Technological measures

Percussive pile driving can be avoided or reduced by using an alternative foundation type or piling method, which should generally reduce noise output.

Alternative foundations include floating bases (which may require some small-scale pile driving to secure the anchor), gravity bases, and suction caissons (Sun et al., 2012). Each type has other environmental costs when compared to piled foundations (e.g. larger seabed footprint and associated impacts to the benthic habitat) which need to be balanced against any noise reduction benefits.

Alternative piling methods are expected to reduce noise output but their feasibility may depend on the seabed composition and water depth. Vibratory pile driving (vibropiling) may be used, either alone or with a limited amount of percussive piling if hard structures are encountered in the sediment, or to assess the bearing capacity of the pile. Ongoing innovation may also yield new techniques, such as the 'Blue Hammer', which piles by displacing a mass of seawater held within a tank on top of the pile, using gas combustion (Fistuca, 2018).

5.2.2. Operational measures

Noise emissions can be reduced by placing acoustic barriers around the piling operation. Various designs have been developed, using air, air bubbles, solid barriers, or combinations of these.

Big bubble curtains (BBC) consist of a perforated hose laid on the seabed to encircle the piling operation. The hose is pumped with compressed air, creating a curtain of rising bubbles that scatter and absorb noise from the pile driving, reducing noise levels by up to 15 dB (Bellmann, 2014) and the displacement area for harbour porpoises by up to 90% (Dähne et al., 2017).

Several systems have also been developed which enclose the pile in a sleeve deployed from the piling vessel (e.g. IHC Noise Mitigation System). This negates the need for (and cost of) an additional vessel to deploy a BBC.

Noise levels can be reduced further still (by up to 24 dB) by deploying more than one noise abatement system (Bellmann, 2014; Dähne et al., 2017).

5.2.3. Activity reduction measures

The overall noise output of windfarm construction can be reduced by installing fewer, larger turbines with higher power outputs (to maintain overall windfarm power output). This has often occurred during the planning process for windfarms as ongoing advances in wind turbine technology have brought larger turbines onto the market.

5.3. Policy options

There is limited scope to reduce noise pollution by installing fewer turbines (activity reduction), while the use of alternative foundations is promising but may have other environmental consequences. Operational measures which use acoustic barriers to reduce noise may therefore be the most effective option in many cases.

Regulatory requirements introduced in Germany (Umweltbundesamt, 2011) have led to unprecedented innovation in acoustic barriers and alternative piling methods for offshore pile driving. These regulations are based on a CAC-type noise limit for the

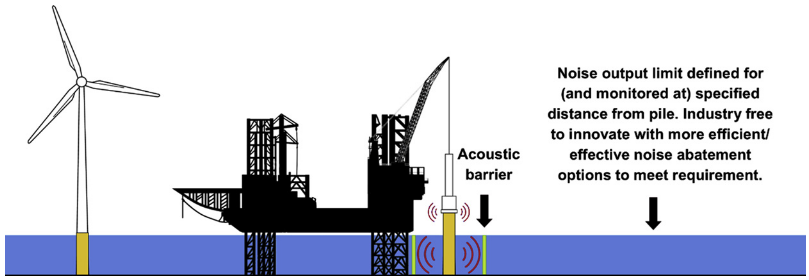

Fig. 3. Schematic illustrating the application of CAC-type requirements for pile driving noise abatement, as pioneered in Germany.

pile driving operation, measured at 750 m, which must be verified in situ for each pile (Fig. 3). Since the regulation directly addresses noise output rather than specifying which technology must be used (i.e. technology control; see Fig. 1), industry has had the flexibility to innovate, developing ever more cost-effective abatement technologies to meet the noise limit.

Windfarm construction has proceeded at pace in German waters, even as government subsidies have declined, and in 2017 Germany approved the first subsidy-free offshore windfarm (Andresen, 2017). This indicates that although the economic cost of compliance with the German regulations may affect the profitability of offshore wind farms, they have not affected their economic viability.

The German approach has substantially reduced noise pollution from pile driving while allowing renewable energy developments to proceed, and therefore represents the most effective noise management model currently available. Further reduction of noise pollution beyond the current noise limit could also be achieved by progressively reducing the limit or by incentivising quieter operations.

6. Seismic airgun surveys for the oil and gas industry

6.1. Context

Seismic surveys are used to map the geological structure beneath the seabed. Surveys are conducted for various commercial and research purposes, but primarily to monitor and prospect for oil and gas reserves. Most surveys use arrays of *seismic airguns*: pistons which discharge bubbles of compressed air into the water column, releasing pulses of high-energy, primarily low-frequency sound. Seismic airguns have been used in the oil and gas industry since the 1960s, when they largely replaced the use of dynamite (Hirst and Rodhouse, 2000).

The effects of seismic airguns observed thus far include: reduced catch rates of several fish, crustacean and mollusc species (Engås et al., 1996; Hirst and Rodhouse, 2000; Weilgart, 2018); behavioural reactions, auditory damage, or reductions in abundance of various fish species (McCauley et al., 2003; Fewtrell and McCauley, 2012; Paxton et al., 2017); displacement of harbour porpoise (Thompson et al., 2013), and fin, humpback, grey and bowhead whales (Richardson et al., 1995); and reduced abundance and increased mortality of zooplankton (McCauley et al., 2017). Given that seismic surveys are globally widespread and may last for weeks or months, and that airgun noise can be detectable at ~4000 km (Nieukirk et al., 2012), the potential for large-scale impacts is clear (Nowacek et al., 2015).

The most promising alternatives to airguns are known as marine vibroseis (see below), however there has been relatively little investment in operationalising these technologies since there has been a lack of regulatory pressure to do so. Thus far, noise abatement measures have been limited, for example recommending that airguns are switched off as the survey vessel navigates between survey lines (JNCC, 2017). The challenge for policymakers in reducing noise from seismic surveys is therefore *how to create regulatory conditions which incentivise the development and application of viable alternative technologies to seismic airguns*.

6.2. Abatement options

6.2.1. Technological measures

The first marine vibroseis systems were developed in the 1960s (Smith and Jenkerson, 1998), and produce lower sound levels than seismic airguns by using a longer, less intense signal. This signal may sweep through relevant acoustic frequencies for seismic exploration (~5–100 Hz) or consist of frequency-coded (pseudo-random) noise (LGL, MAI, 2011). The signal is produced by one or more acoustic transducers powered by electro-mechanical or hydraulic systems (LGL, MAI, 2011).

Marine vibroseis generates lower sound levels and produces less noise at extraneous frequencies (> 100 Hz) for seismic surveys, and so is expected to substantially reduce impact on marine life (Duncan et al., 2017), although in situ studies of effects are lacking (Okeanos Foundation, 2010). Reports on marine vibroseis commissioned by the oil and gas industry have concluded that "tests using… marine vibrator systems have shown seismic data results that are approximately equal to or better than those obtained using air guns and explosives" (Spence et al., 2007) and that "use of MarVib [marine vibroseis] sources rather than airguns is expected to reduce most types of environmental impacts in all habitats and environments" (LGL, MAI, 2011).

Although marine vibroseis systems have been successfully trialled in various shallow-water, deep-water and transitional environments (e.g. Smith and Jenkerson, 1998; LGL, MAI, 2011; Musarra, 2017), they are not presently in wide commercial use. This is likely due to a lack of demand: the seismic airgun is a proven and reliable technology, and without economic incentives to use quieter technologies, there is no basis for the commercial market necessary to support their development and application.

6.2.2. Operational measures

Operational measures which reduce the noise output of seismic airgun surveys are limited, e.g. using the lowest feasible sound levels for the survey, and ceasing the firing of airguns as the survey vessel transits between survey lines (JNCC, 2017).

6.2.3. Activity reduction measures

Other than declining consent for the activity altogether (see below), noise abatement via activity reduction can be achieved by ensuring that data-sharing requirements are in place which prevent repeated surveys of the same area due to commercial confidentiality restrictions (Nowacek et al., 2015).

6.3. Policy options

The scope for noise abatement of seismic airgun surveys via operational measures and by improving data sharing requirements is limited. It therefore seems that technological alternatives to seismic airguns or substantial reductions in survey activity will be required to achieve significant noise abatement.

CAC-type requirements on industry to reduce noise levels could be effective if they are sensitive to the fact that time will be needed to scale

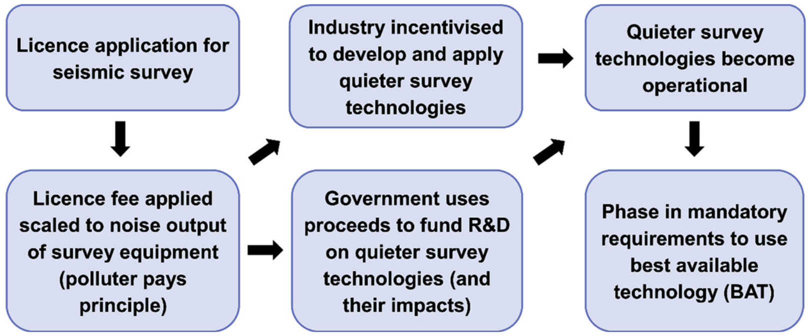

Fig. 4. Proposed roadmap for achieving noise abatement in the seismic surveying industry.

up alternative technologies, since systems such as marine vibroseis are not currently operational at commercial scale. Regulators could follow the German pile-driving example (see Section 5) and specify a maximum noise output for survey systems which would effectively prohibit high-power seismic airguns and require the use of alternative technologies. However, a time lag in enforcement would be needed to allow for technological development.

In these circumstances, an incentive-based approach may be more effective than CAC measures. Progressive levies on seismic surveys based on noise output could be used to incentivise quieter technologies (Fig. 4). This would recognise the environmental costs of seismic surveys which are not currently accounted for economically (externalities), and would follow the *polluter pays principle* (PPP), which places the cost of environmental remediation on those who pollute the environment (as prescribed by, inter alia, the 1992 Rio Declaration and the European Union). The revenue raised by the levy could be invested by government to support the development of full-scale alternative technologies, and in situ studies of their effects on marine life. Such progressive levies would also encourage industry to innovate with quieter and more cost-effective technologies. Similar approaches have been successful for other sources of marine environmental impact, for example the UK Aggregates Levy, which discouraged the extraction of primary marine aggregates for the construction industry and funded scientific research to improve management. Once quieter survey technologies have become operational, CAC-type (mandatory) requirements could then be enforced to ensure uptake across the industry, obliging operators to use the best available technology (BAT) in terms of minimal noise output (Fig. 4).

A final option for achieving noise abatement is to decline consent for survey activity. In the US, impacts of noise pollution on marine mammals were central to a decision by the Bureau of Ocean Energy Management (under the Obama administration) to deny permits for oil and gas exploration using seismic surveys in the mid- and south-Atlantic coast (BOEM, 2017), a decision which has since been overturned by the Trump administration. In the longer term, the wider issue of climate change caused by fossil fuel combustion may lead to noise abatement indirectly, if policies designed to ‘keep it in the ground’ lead to a decline in exploration activity and correspondingly lower noise pollution.

7. Other noise sources

The three industries highlighted in the case studies above are major contributors to underwater noise pollution, however, there are many other anthropogenic noise sources which warrant more detailed consideration than is possible in this paper. These include smaller (e.g. fishing, recreational) vessels, military sonar, acoustic deterrent devices (ADDs), explosives, oceanographic surveys, and emerging issues such as decommissioning of oil and gas infrastructure and deep-sea mining.

8. Conclusions

The three case studies highlighted in this paper have identified viable paths forward for policymakers to progressively steer each industry toward less polluting technologies and ways of operating. By making judicious use of command-and-control and incentive-based measures, carefully designed policies can lead to effective noise abatement while avoiding unnecessary disruption, and can unleash the innovative potential of industry to overcome the remaining technological challenges.

As climate change and increasing human use of the oceans put growing strain on marine ecosystems, noise abatement presents a relatively tractable policy option to help reduce the cumulative burden of anthropogenic pressure on Earth’s marine habitats.

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