REPORT

Noise budget for Seismic Activities in the Dutch North Sea

A cost-benefit analysis

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Samenvatting

Sinds de Jaren 50 zijn grootschalige seismisch onderzoeken een belangrijke bron van onderwatergeluid in de Noordzee. Sindsdien nemen de activiteiten zoals scheepvaart, sonar, ontmanteling van explosieven en recentelijk de aanleg van offshore windparken op de Noordzee toe. Het is nu algemeen aanvaard dat geluid dat door deze activiteiten wordt geproduceerd een negatieve invloed kan hebben op de mariene fauna. Onderwatergeluid kan ofwel resulteren in onmiddellijke sterfte van individuele mariene organismen als gevolg van drukverschillen of (tijdelijke) gehoorschade, ofwel negatieve gevolgen hebben voor de conditie van de soort door verstoring en/of maskering.

In verschillende wettelijke en beleidskaders die zich richten op de bescherming van het mariene milieu, komt de vermindering van onderwatergeluid aan bod. Met name de Europese Kaderrichtlijn Mariene Strategie (KRMS) definieerde antropogeen onderwatergeluid formeel als een bron van vervuiling (EU, 2008). De KRM streeft naar een goede milieutoestand (GMT) van de Europese maritieme wateren in 2020 (EU, 2008). De GMT wordt gedefinieerd in termen van elf descriptoren, waarvan er één onderwatergeluid is (descriptor 11). De KRM roept de lidstaten op maatregelen te identificeren die moeten worden genomen om een goede milieutoestand te bereiken of te behouden (artikel 13/1), maar ook om "ervoor te zorgen dat de maatregelen kosteneffectief en technisch haalbaar zijn" door effectbeoordelingen en kosten-batenanalyses uit te voeren (MKBA) voorafgaand aan de invoering van een nieuwe maatregel (artikel 13/3).

Momenteel zijn er geen formele KRM-maatregelen voorgesteld met betrekking tot onderwatergeluid gerelateerd aan seismisch onderzoek. Nederland overweegt echter om een geluidsbudget in te voeren voor seismisch onderzoek. Het doel van dit rapport is om verschillende alternatieven te identificeren die kunnen worden overwogen om de geluidsbelasting (een zogenaamd geluidsbudget) te verminderen voor grootschalige seismische onderzoeken op zee op het Nederlands Continentaal Plat. Daarnaast worden de gerelateerde ecologische, economische en sociale kosten en baten van de maatregelen besproken.

Een beperking in de analyses is de grote mate van onzekerheid met betrekking tot een aantal belangrijke aannames en uitgangspunten.

- De toekomstprognose voor seismisch onderzoek: deze is afhankelijk van meerdere factoren waarvan regulering m.b.t. geluid er slechts één is;
- De ecologische baten zijn moeilijk tot niet te waarderen in geld:
  - De ecologische fysieke effecten (zowel direct als indirect) zijn moeilijk te bepalen door een gebrek aan wetenschappelijke kennis op specifiek het gebied van populatiedynamica ten gevolge van (seismisch) onderwatergeluid;
  - Er zijn geen kengetallen om deze ecologische effecten te waarderen;
- Het is onbekend bij welke ondergrens van een geluidsbudget er nadelige gevolgen optreden voor de offshore sector en tegelijkertijd is het onbekend bij welke bovengrens er significante nadelige ecologische impact op treedt.

Door een gebrek aan data waardoor inherente onzekerheid ontstaat bij het kwantificeren van de effecten van de invoering van een geluidsbudget, kon daarom geen volwaardige MKBA worden uitgevoerd. Desalniettemin is het doel van deze studie om objectieve informatie te verschaffen die kan worden gebruikt om te overwegen of een geluidsbudget een effectieve manier zou kunnen zijn om de ecologische impact van (grootschalige) seismische onderzoeken te verminderen of te beperken en wat de kosten en baten van een dergelijk geluidsbudget zou kunnen zijn. De resultaten van het onderzoek worden hieronder samengevat.

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Referentiescenario
Uit interviews blijkt dat de industrie plannen heeft om in de komende jaren een beperkt aantal 3D-surveys uit te voeren, met een totale geschatte oppervlakte van 4.600 km^2. De omvang van het gebied dat de komende jaren wordt onderzocht, is moeilijk nauwkeurig te voorspellen, aangezien dit sterk afhankelijk is van de olie- en gasprijzen, het economische klimaat en het Nederlandse energiebeleid. Ook zonder de introductie van aanvullende maatregelen, zoals een geluidsbudget, is seismisch onderzoek gereguleerd door bestaande afspraken, beleid en wetgeving. Momenteel worden veel gebruikte verzachtende maatregelen toegepast tijdens seismisch onderzoek, zoals een 'soft start, waarbij het geluid langzaam wordt opgevoerd en de dieren worden weggejaagd. Door het toepassen van deze maatregel wordt directe fysieke schade als gevolg van seismisch onderzoek op mobiele soorten zoals zeezoogdieren en pelagische vissen vermeden. Het effect op andere organismen die niet aan het geluid kunnen ontsnappen, is nog grotendeels onbekend.

Voor seismische projecten moet een Nederlandse natuurbeschermingsvergunning worden aangevraagd. Bij het aanvragen van een vergunning zal een ecologische effectbeoordeling of een passende beoordeling moeten worden gemaakt om de ecologische impact te onderzoeken.

Beleidsalternatieven voor een geluidsbudget
In deze studie worden de volgende alternatieven voor een geluidsbudget gepresenteerd:

1. Regulering door middel van een vaste geluidslimiet
2. Regulering door middel van een technische eis
3. Regulering door middel van een geluidsbudget in vierkante kilometers
4. Regulering door middel van een geluidsbudget op dierenverstoringsdagen

Uit dit onderzoek blijkt dat van de vier alternatieven de eerste twee alternatieven niet haalbaar of wenselijk worden geacht en daarom beperkt worden beoordeeld. Een vaste geluidslimiet is niet haalbaar omdat dit het praktisch onmogelijk maakt om nog seismisch onderzoek uit te voeren. Dit druist in tegen het Nederlandse kleine velden beleid. Het verplicht stellen van een bepaalde techniek staat innovatie in de weg, en het gebruik van de best beschikbare techniek is al vastgelegd in het Noordzee Akkoord. Daarnaast zijn er maar beperkte alternatieve technologieën beschikbaar om geologische gegevens op zee te verkrijgen.

Een geluidsbudget in vierkante kilometers (alternatief 3) (bv. Op basis van de gemiddelde oppervlakte van eerdere onderzoeken) kan ervoor zorgen dat de ecologische impact even groot of lager is dan in het verleden. De meest eenvoudige manier om dit te doen, is door het vaststellen van een jaarlijks budget van een vast (of deels flexibel) aantal vierkante kilometers. Een geluidsbudget op basis van vierkante kilometers gaat echter voorbij aan het feit dat de duur van een seismisch onderzoek een grotere impact heeft op het milieu dan het oppervlak in relatie tot verstoring van de bruinvis. En als het toegestane oppervlak is vastgesteld, is er geen prikkel om te zoeken naar ecologisch geoptimaliseerde technieken, behalve om de instandhoudingsdoelen van mogelijke nabijgelegen Natura 2000-gebieden te realiseren. Dit laatste is echter al een vereiste.

Een ecologisch betere methode zou zijn om een budget te definiëren op basis van (bruinvis) verstoringsdagen (alternatief 4) afgeleid van de gemiddelde belasting met geluid in het verleden. Een bruinvisverstoringsdag is het product van het aantal verstoorde zeezoogdieren (in dit geval bruinvissen) per dag van verstoring door seismisch onderzoek en het aantal dagen dat de verstoring plaatsvindt (rekening houdend met het verschil in seizoenen en de duur van de verstoring per verstoringsdag). Op deze manier kan de gebruiker het seismisch onderzoek op een dusdanige manier optimaliseren zodat het onderzoek zo min mogelijk storingsdagen "kost". Afhankelijk van hoe het onderzoek wordt uitgevoerd, kan de exploitant zelfs een groter gebied bestrijken met dezelfde ecologische impact. Er is echter veel onzekerheid met betrekking tot het berekenen van de verstoring veroorzaakt door seismisch onderzoek.

De ecologische en economische voordelen van beide alternatieven zijn sterk afhankelijk van de beperking die wordt gesteld in vierkante kilometers of aantal storingsdagen. In dit stadium bestaat er echter te veel onzekerheid over de effecten van seismisch onderzoek op mariene soorten om een effectief geluidsbudget te bepalen.

Kosten en baten van een geluidsbudget
Omdat er zoveel onzekerheid is over zowel de relatie tussen een geluidsbudget en seismisch onderzoek, alsook de relatie tussen seismisch onderzoek en verstoring, was een volledige MKBA op verschillende varianten van een geluidsbudget niet mogelijk. In plaats daarvan kijkt de MKBA naar twee extreme scenario's:

- In het eerste extreme scenario worden er geen verdere beperkingen opgelegd aan seismisch onderzoek in termen van geluid (dit is in feite het referentiescenario). Dit brengt ecologische risico's met zich mee, geeft de overheid minder controle over de (planning en hoeveelheid) onderzoeken en zou kunnen leiden tot een geschatte en indicatieve range van 54 tot 280 duizend bruinvisverstoringsdagen.
- In het tweede extreme scenario worden geen seismische onderzoeken meer gehouden op het NCP vanwege de implementatie van een geluidsbudget. De implicatie zou zijn dat er meer gas moet worden geïmporteerd, wat leidt tot ongeveer 4,8 miljard euro aan kosten als gevolg van hogere emissies van NO_x en broeikasgassen en verloren overheidsinkomsten, terwijl de voorzieningszekerheid wordt verzwakt.

Bij het invoeren van een geluidsbudget op basis van het historisch gemiddelde van seismische onderzoeken zijn er geen ecologische voordelen in termen van vermeden verstoringsdagen van zeezoogdieren (aangezien het aantal verstoringsdagen hetzelfde zou moeten zijn als in het verleden). Er zou echter een ecologisch voordeel kunnen zijn in termen van de impact op populaties. De introductie van alleen een geluidsbudget leidt naar verwachting ook niet tot (substantieel) hogere economische kosten. Het resterende argument voor een geluidsbudget op basis van 'bestaand gebruik' zou zijn dat het meer bescherming geeft tegen een concentratie van verstoringen (hetzij door combinaties van grote surveys of door cumulatie met de offshore windsector) en meer controle voor regelgevende instanties in het vergunningsproces.

Aanbevelingen
Op basis van de resultaten van dit onderzoek komen we tot de volgende aanbevelingen:

- Bij het invoeren van een geluidsbudget of andere methode van regulering van seismisch onderzoek is het belangrijk dat het geluidsbudget flexibel is om met de huidige onzekerheden om te gaan. Bij de beslissing om een geluidsbudget te implementeren, moet een beginwaarde (in km2 of in storingsdagen) worden bepaald en overeengekomen waarover periodiek onderhandelt kan worden. Het geluidsbudget kan worden aangepast aan veranderende omstandigheden (zoals verwachte bouw van windparken op zee, economische cyclus, nieuwe technologieën en nieuwe informatie over effecten). Vanwege de mate van onzekerheid is het creëren van flexibiliteit zowel gunstig voor de toezichthouders als voor de industrie.
- Om te kunnen beslissen over een effectief geluidsbudgetniveau (zoals het aantal bruinvisverstoringsdagen) moet eerst het volgende worden bereikt:
    - Specifiek voor seismisch onderzoek moet een deugdelijk model worden ontwikkeld dat de impact van seismisch onderzoek op de omgeving zo nauwkeurig mogelijk kan inschatten.
    - Er moet een populatiemodel worden ontwikkeld of aangepast om de impact van het voorspelde onderwatergeluid op de populatie van gevoelige soorten te bepalen (te beginnen met de bruinvis)
    - De invoerparameters voor deze modellen moeten worden afgesproken. Mogelijk kunnen de werkgroepen die voor het Noordzee-akkoord zijn opgericht, worden gebruikt om dit te bespreken

    - Onderzoek naar de ecologische impact van piekverstoring bij het combineren van meerdere seismische onderzoeken is nodig.
    - Houd er rekening mee dat het bovenstaande een behoorlijk tijdrovend proces is dat enkele jaren kan duren.
- Om de inzet en vooral de verbetering van BBT (Best beschikbare technieken) voor seismisch onderzoek te stimuleren, is het raadzaam om regelgeving met betrekking tot BBT op Europees of OSPAR-niveau te implementeren.
- Het invoeren van een geluidsbudget kan ook een positief effect hebben op andere mariene soorten dan zeezoogdieren zoals vogels, vissen, schildpadden en bodemorganismen. Het wordt aanbevolen om ook de effecten van andere gevoelige soorten te onderzoeken, met name niet-mobiele soorten. Het wordt aangeraden om ook de effecten van andere gevoelige soorten, met name niet-mobiele soorten, te onderzoeken en een studie uit te voeren naar de correlatie tussen antropogene activiteiten en soortverspreiding/ sterfte (Ijsseldijk & Doeschate, 2020).
- Als er eenmaal een geluidsbudget is, moet worden bepaald op welke manier het budget wordt verdeeld tussen belanghebbenden. Er zijn verschillende opties, zoals First Come First Serve (FCFS), veilen, grandfathering, cap-and trade, onderhandeling binnen de brancheorganisatie (NOGEPA), etc. Elk mechanisme heeft zijn voor- en nadelen. Dit dient besproken te worden met organisaties, zoals NOGEPA.
- Het is nog onduidelijk of het gecombineerde geluid van alle huidige activiteiten, inclusief de bouw van windmolenparken op zee, binnen de veerkracht van de populaties van verschillende soorten zal vallen. Geluid moet daarom niet per sector of per activiteit worden bekeken, maar in combinatie met verschillende (impuls) activiteiten, zowel ruimtelijk als in tijd. Het verdient aanbeveling om voor een combinatie van alle activiteiten een geluidsbudget in te voeren, in plaats van een budget per activiteit afzonderlijk te definiëren.
- Indien het niet mogelijk of wenselijk blijkt om de verschillende sectoren in een gecombineerd geluidbudget te formuleren is het raadzaam om ervoor zorg te dragen dat er geen gelijktijdige grootschalige activiteiten met een grote impact met betrekking op geluidverstoring plaatsvinden. Dit kan geborgd worden in bijvoorbeeld een gezamenlijk overleg tussen de overheid en de verschillende sectoren (bijvoorbeeld in de gremia zoals gebruikt voor het Noordzee Akkoord). Een mogelijke vervolgstap is het onderzoeken van de mogelijkheden om een (internationale) ruimtelijke planningstool te ontwikkelen waarbij het duidelijk is wanneer welke activiteit waar plaats vindt.

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Summary

As early as the 1950's large scale seismic surveys are a major source of underwater noise in the North Sea. Since then activities in the North Sea, such as shipping, sonar, dismantling of explosives and recently the construction of offshore wind farms, are increasing. It is now widely accepted that the sound, or noise, produced by these activities can have a negative impact on the marine fauna. The impact can either result in immediate mortality of individual marine animals due to pressure differences or (temporary) hearing damage, or reduced fitness because of disturbance and/or the masking of sound.

In several legal and policy frameworks focussing on the protection of the marine environment, the reduction of underwater noise is addressed. In particular, the European Marine Strategy Framework Directive (MSFD) formally defined anthropogenic underwater noise as a source of pollution (EU, 2008). The MSFD aims to achieve Good Environmental Status (GES) of the European maritime waters by 2020 (EU, 2008). GES is defined in terms of eleven descriptors, one of which is underwater noise (descriptor 11). The MSFD calls for Member States to identify measures to be taken to achieve or maintain Good Environmental Status (Article 13/1), but also to "ensure that measures are cost-effective and technically feasible" by carrying out impact assessments and cost benefit analyses (CBA) prior to the introduction of any new measure (Article 13/3).

At present no formal MSFD-measures have been proposed regarding underwater noise related to seismic surveys. However, The Netherlands is considering introducing a noise budget for seismic surveys. The purpose of this report is to identify various alternatives that can be considered to reduce noise impacts (a so called noise budget) for large scale offshore seismic surveys on the Dutch Continental Shelf. In addition, the related ecological, economic and social costs and benefits of the measures are discussed.

Due to a lack of data causing inherent uncertainty in quantifying the impacts of the introduction of a noise budget, a full-fledged CBA could not be conducted. Nevertheless the aim of this study is to provide objective information that can be used to consider whether a noise budget could be an effective way to reduce or limit the ecological impact of (large scale) seismic surveys and what the costs and benefits of such a noise budget could be. The results of the study are summarised below.

Reference scenario
Based on interviews it appears that the industry has plans to carry out a limited number of 3D surveys in the next 5-10 years, with a total estimated surface area of 4,600 km^2. It is hard to accurately forecast the size of the area that will be surveyed in the coming years, as this highly depends on the oil and gas prices, the economic climate and Dutch energy policies. Even in the absence of additional measures, seismic surveying is subject to existing agreements, policy and regulation. At present, commonly used mitigation measures are applied during seismic surveys such as a soft start which scares the animals away, thus avoiding direct physical harm due to seismic surveys on mobile species such as marine mammals and pelagic fish. The effect on other organisms that cannot escape the noise, is as of yet largely unknown.

All seismic projects will need to apply for a Dutch Nature Conservation permit. This entails an assessment of the ecological impact and of the conservation goals of the possibly effected Natura 2000 areas and the concerning protected species.

Policy alternatives for a noise budget
The following noise budget alternatives are presented in this study:

1. Regulating by means of a fixed noise limit

2. Regulating by means of a technical requirement
3. Regulating by means of a noise budget in square kilometres
4. Regulating by means of a noise budget in animal disturbance days

This study shows that of the four policy alternatives, the first two alternatives are not deemed technically or economically feasible and are therefore not further assessed. Technically the alternatives are not feasible as there are limited alternative technologies that can be used to acquire geological data at sea. The technologies that do exist have not yet been used on a commercial scale.

Alternative 3, a noise budget in square kilometres (e.g. based on the average area of previous surveys) can ensure that the ecological impact will be as great as, or lower than it has been in the past The most straight forward way to do this, is by means of an annual budget of a fixed (or partly flexible) number of square kilometres. However, a noise budget based on square kilometres ignores the fact that the duration of a seismic survey has a larger impact on the environment than surface area in relation to disturbance for the harbour porpoise. And when the allowed surface area is fixed there is no incentive to search for ecologically optimised techniques, other than to fulfil the conservation goals of possible nearby Natura 2000-areas. However, this is already a requirement.

An ecologically better method would be to define a budget based on (harbour porpoise) disturbance days (alternative 4) derived from the average past impact. A harbour porpoise disturbance day is the product of the number of disturbed mammals (in this case harbour porpoises) per day of disturbance by seismic surveys and the number of days during which the disturbance takes place (keeping in mind the difference in seasons and the duration of the disturbance per disturbance day).This method allows for an operator to optimise the survey in such a way that it “costs” as less disturbance days as possible. Depending on how the survey is conducted, the operator may even be able to cover a larger area with the same amount of ecological impact. However, there is a lot of uncertainty related to calculating the disturbance caused by seismic surveys.

The ecological and economic benefits of both alternatives highly depend on the limitation that is set in square kilometres or number of disturbance days. However, at this stage there is too much uncertainty surrounding the impacts of seismic surveys on marine species to determine an effective noise budget.

Costs and benefits of a noise budget

Because there is so much uncertainty surrounding both, the relation between a noise budget and seismic research, as well as the relation between seismic research and disturbance, a ‘proper’ CBA on different variations of a noise budget was not possible. Instead, the CBA looks at two extreme scenarios:

- In the first extreme scenario, there are no further restrictions imposed on seismic surveys in terms of sound (this is effectively the reference scenario). This poses ecological risks, gives the authorities less control over the (planning and amount of) surveys and could lead to an estimated and indicative range of 54 to 280 thousand harbour porpoise disturbance days.
- In the second extreme scenario, no more seismic surveys are held on the DCS due to the implementation of a noise budget. The implication would be that more gas needs to be imported, leading to approximately EUR 4.8 billion in costs due to higher emissions of NO_x and GHG as well as lost State revenues, while weakening the security of supply.

When introducing a noise budget based on the historic average of seismic surveys there are no ecological benefits in terms of avoided marine mammal disturbance days (since the number of disturbance days is supposed to be the same as in the past). However, there could be an ecological benefit in terms of the impact on populations. The introduction of a noise budget alone is also not expected to lead to (substantially) higher economic costs. The remaining argument in favour of a noise budget based on ‘existing use’ would be that it gives more protection against a concentration of disturbance (either through combinations of large surveys or through cumulation with the offshore wind sector) and more control for regulatory bodies in the permitting process.

Recommendations

Based on the results of this study, we come to the following recommendations:

- When introducing a noise budget or other means of regulating seismic surveys then it is important that the noise budget is flexible to deal with the present uncertainties. If deciding to implement a noise budget, an initial value (either in km^2 or in disturbance days) needs to be determined and agreed to negotiate periodically. The noise budget can be modified to accommodate changing circumstances (such as expected construction of offshore wind farms, economic cycle, new technologies and new information on impacts). Due to the level of uncertainty creating flexibility is both beneficial for the regulators as well as the industry.
- Before being able to decide on an effective noise budget level (such as the amount of harbour porpoise disturbance days) the following needs to be accomplished first:
    - A proper sound model needs to be developed specifically for seismic surveys that can estimate the impact of seismic surveys on the environment as accurately as possible.
    - A population model needs to be developed or customized to determine the impact of the predicted underwater noise on the population of sensitive species (to start with the harbour porpoise)
    - The input parameters for these models will need to be agreed upon. Potentially the working groups created for the North Sea Agreement could be used to discuss this
    - Conduct further research into the ecological impact of peak disturbance when combining multiple surveys.
    - Do note that the above is quite a time-consuming process which can take a few years.
- To incentivise the deployment and especially the improvement of BAT for seismic surveys, it is advisable to implement regulation on, at least, European or OSPAR level.
- Little is known about the effects of underwater noise on other marine species besides marine mammals. Also, knowledge on impacts on the marine ecosystem level are scarce. However, reducing underwater noise or implementing a noise budget could also have a positive effect on marine species other than marine mammals such as birds, fish, turtles and benthic organisms. It is advised to also investigate the impacts of other sensitive species especially non-mobile species and conduct a study on the correlation between anthropogenic activities and species distribution/mortality (Ijsseldijk & Doeschate, 2020).
- Once there is a noise budget, the way the budget is allocated between interested parties needs to be determined. Different options exist, such as First Come First Serve (FCFS), auctioning, grandfathering, cap and trade, negotiation within the industry organisation (NOGEPA), etc. Each mechanism has its pros and cons. This needs to be discussed with(in) organisations, such as NOGEPA.
- It is still unclear whether the combined noise from all the current activities, including the construction of offshore windfarms, is going to be within the resilience of the populations of different species. Noise should therefore not be looked at per sector or per activity, but in combination with different activities, both spatially and in time. It is recommended to introduce a noise budget for a combination of all activities, instead of defining a budget per individual activity.
- If a multiple sector combined noise budget is not possible or desirable, it is advisable to ensure that no simultaneous large-scale activities with a major impact regarding noise disturbance take place. This can be safeguarded, for instance, in joint consultation between the government and the various sectors (for example in the bodies used for the North Sea Agreement). A possible follow-up step is to investigate the possibilities of developing an (international) spatial planning tool that visualises when and where which activity will take place.

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Abbreviation list

ADD	: Acoustic Deterrent Device
BAT	: Best Available Technique
CBA	: cost benefit analysis
CCS	: Carbon Capture and Storage
DCS	: Dutch Continental Shelf
EP	: Environmental plan
ESA	: Endangered Species Act
GES	: Good Environmental Status
Hp	: Harbour porpoise
IOGP	: International Association of Oil & Gas Producers
JNCC	: Joint Nature Conservation Committee
KEC	: Kader Ecologie en Cumulatie
MMO	: Marine mammal observer
MMPA	: Marine Mammal Protection Act
MSFD	: Marine Strategy Framework Directive
NMFS	: National Marine Fisheries Service
NOPSEMA	: National Offshore Petroleum Safety and Environmental Management Authority
PAM	: Passive acoustic monitoring
PEPANZ	: Petroleum Exploration and Production Association of New Zealand
Psi	: Pounds per square inch
PSO	: Protected species observer
PTS	: Permanent Threshold Shift
RVO	: Remote Operating Vehicle
SDS	: Streamer Dual Source
SEL	: Single Exposure Level
TTS	: Temporary Threshold Shift
VSP	: Vertical seismic profiling

1 Introduction

1.1 Purpose of this report

As early as the 1950's large scale seismic surveys are a major source of underwater noise in the North Sea. Since then activities, such as shipping, sonar, dismantling of explosives and recently the construction of offshore wind farms, in the North Sea area are increasing. It is now widely accepted that the sound, or noise, produced by these activities can have a negative impact on the marine fauna. The impact can either result in immediate mortality of individuals due to pressure differences or (temporary) hearing damage, or reduced fitness because of disturbance and/or the masking of sound.

In several legal and policy frameworks focussing on the protection of the marine environment, the reduction of underwater noise is addressed. In particular, the European Marine Strategy Framework Directive (MSFD) formally defined anthropogenic underwater noise as a source of pollution (EU, 2008). The MSFD aims to achieve Good Environmental Status (GES) of the European maritime waters by 2020 (EU, 2008). GES is defined in terms of eleven descriptors, one of which is underwater noise (descriptor 11). The MSFD calls for Member States to identify measures to be taken to achieve or maintain Good Environmental Status (Article 13/1), but also to "ensure that measures are cost-effective and technically feasible" by carrying out impact assessments and cost benefit analyses (CBA) prior to the introduction of any new measure (Article 13/3).

At present no formal MSFD-measures have been proposed regarding underwater noise related to seismic surveys. However, The Netherlands is considering introducing a noise budget for seismic surveys. The purpose of this report is to identify various alternatives that can be considered to reduce noise impacts (a so-called noise budget) for large scale offshore seismic surveys on the Dutch Continental Shelf (DCS). In addition, the related ecological, economic and social costs and benefits of the measures are discussed. Though this report is not a standard CBA, due to a lack of necessary data, this report is aimed to provide objective information that can be used to consider whether a noise budget could be an effective way to reduce or limit the ecological impact of (large scale) seismic surveys and what the related costs and benefits of such a noise budget could be.

1.2 Methodology and limitations of this study

The idea of a possible implementation of a noise budget for seismic surveys in the North Sea was introduced in the North Sea Agreement (OFL, 2020), the Conservation plan for the Harbour Porpoise (Ministry of Agriculture, Nature and Food Quality, 2020) and the "redeneerlijn seismiek" (internal document RWS/LNV, 2019). However, it is unclear what the noise budget will have to include for seismic surveys and whether such a measure is cost-effective and technically feasible. This report therefore sets out the various policy alternatives for a noise budget and their social, ecological and economical costs and benefits.

Seismic surveys are usually related to the exploration of oil and gas. However, seismic surveys can be applied at different scales and for different purposes. Depending on how the seismic survey is conducted the impact on the environment can be different. In addition, research on underwater noise is still ongoing and the effects on the marine environment are not always well understood. Therefore, the following delineations were applied in this study:

- Only large scale (3D or 4D) offshore seismic surveys for oil and gas exploration are considered, small (2D) studies of only a few days, or vertical seismic profiling (VSP) surveys are not in the scope of this study as no significant impacts om population levels are expected. Additionally, shallow seismic surveys using subbottom profilers such as boomers, pingers and chirp sonar are not included. This type of seismic surveys use higher frequencies (> 1000 Hz) and have a limited spatial impact.

- This study does not include possible seismic surveys needed for CCS (Carbon Capture and Storage). It is of yet unclear if seismic surveys are needed to facilitate CCS in depleted offshore underground gas-reservoirs and, if so, what the extent of these surveys will be.
- Only impulsive noise as a result of the airguns is taken into account, other (continuous) noise sources (like shipping noise) are not.
- The ecological indicators used to determine the ecological impact of a noise budget are limited to species with known distribution and sensitivity to underwater noise.
- Only existing technical measures and proven technologies are considered
- Geographically the study limits itself to the DCS outside of the 3-mile zone.
- Economic limitations: The impact of regulation on seismic surveys performed by the oil and gas industry is the subject of this study; excluded are seismic surveys done for other purposes (such as scientific) as these are relatively minor or not expected in the near future.
- Within the oil and gas industry, the focus in terms of impact is on natural gas production as oil production on the DCS is declining.
- Natural gas demand is assumed to be autonomous for the purpose of this study, meaning that any natural gas not produced from the DCS as a result of regulatory measures must be imported (and not replaced by other energy carriers or avoided by energy efficiency measures).

1.2.1 Interviews

This study is based on literature review and interviews with stakeholders with different roles related to off-shore seismic surveys and underwater noise. The interviews were structured along a questionnaire. Depending on the role of the interviewee the questions differed. The results of the interviews have been incorporated in this report. Table 1-1 gives an overview of the different stakeholders that were interviewed. Annex

Table 1-1 Stakeholders interviewed per role related to the proposed measures

Role related to measures	Stakeholder
Association and off taker/user	NOGEPA, EBN
Regulators and legislators	Ministry of Agriculture, Nature and Food (LNV), Rijkswaterstaat
Supplier of airguns	Teledyne Marine Seismic
Expert	TNO
Other with practical application experience of a noise budget	Eneco energy, Pondera Consultancy

1.2.2 CBA methodology

As stated before, the MSFD requires that for each new measure an impact assessment is performed, including a cost benefit analysis. For this reason, the report has been structured in accordance with the Dutch guidelines as issued by CPB/PBL on how to perform cost benefit analyses (Romijn and Renes, 2013) . The report follows the steps usually taken in a CBA process, as depicted below in Figure 1-1. As chapter 2 and 3 will explain further, a complication in this study is a lack of data on a number of issues. The implication of this is that that there is lot of inherent uncertainty in quantifying, let alone valuation, of impacts of this intervention. Nevertheless, in this study, the CBA approach is followed as far as possible.

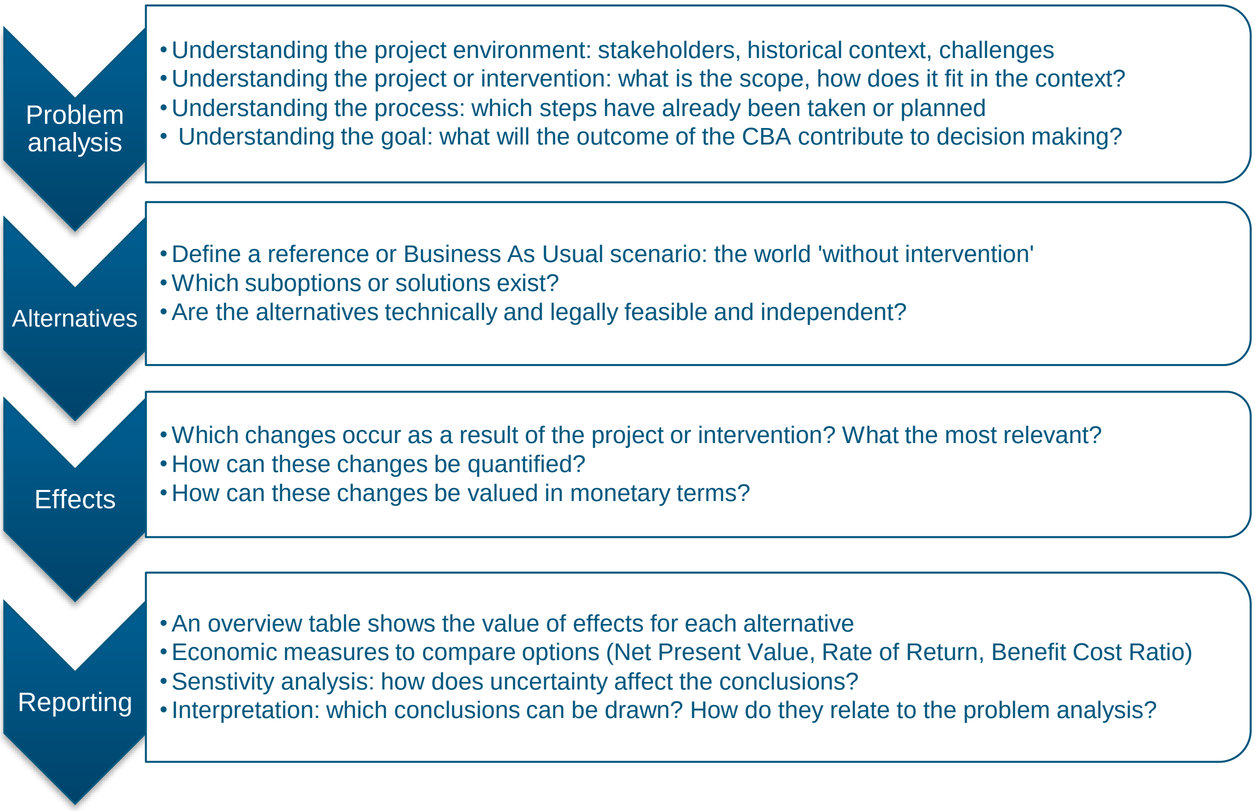

Figure 1-1 - Steps in a Cost Benefit Analysis (based on Romijn and Renes, 2013, adapted by Royal HaskoningDHV)

When performing a CBA, we take the following considerations into account:

- A CBA is best put to use when there are clear differences between different options: we have discussed, selected and studied a number of relevant options in this analysis.
- A CBA should start with a step that is often overlooked: What is the problem? Why is this intervention considered and what would happen without it? Chapter 2 is dedicated to these questions.
- Ideally, stakeholders representing different views and interests are involved in the process to facilitate joint fact finding. A transparent and inclusive process ensures that the approach can be trusted. In our interviews, we have ensured to collect different views, both from those affected by regulation of seismic surveys and those seeking to control ecological impacts.

1.3 Report structure

The sections of this report have been structured in the following way. Chapter 2 sets out the problem analysis which provides the basis of information needed for this study. The problem analysis includes a summary of information. More detailed background information, which was collected as part of the study, needed to gain a proper understanding of the topic, is presented in the Appendices, which include descriptions of XYZ. Chapter 3 describes the baseline alternative. Chapter 4 discusses different alternatives for the implementation of a noise budget. Chapter 5 describes the cost and benefits of a noise budget in relation to the baseline alternative and chapter 6 contains conclusions and recommendations.

2 Problem analysis

The goal of offshore seismic surveys is to obtain an (detailed) image of the layers of rock below the seabed for geologic features to indicate the presence of oil and/or gas or to monitor e.g. the behaviour of stored CO_2. This is done by means of loud, repetitive sound blasts produced by airguns. The sound produced can travel hundreds of kilometres through the marine environment. A limiting factor for sound propagation is the water depth. As the North Sea is quite shallow, on average 94 metres deep, a sound propagation of maximum 50 kilometres can be assumed. Marine seismic surveys are also used by the military, marine and offshore extractive industries and academic researchers for a variety of other purposes. These include scientific studies of the earth's geological history, the identification of national maritime zones and boundaries offshore, assessment of seabed foundations for offshore construction and accurate placement of offshore renewable energy infrastructure.

It is well known that underwater sound produced by anthropogenic activities can be a problem for marine life ranging from immediate mortality, shifting hearing thresholds to a change in behaviour. As such underwater noise is included in indicator 11 of the MSFD.

The "Dutch Nature Conservation Law" ensures that the ecological values are not significantly compromised by activities in the marine environment, as the initiator is obligated to perform an ecological impact assessment and apply for a nature permit if there are significant impacts on protected species and/or protected areas which cannot be ruled out.

The following paragraphs will elaborate on the characteristics of seismic sound, the impact on marine life, and the relevant national and international legislation. The last paragraph will depict the relation between the current legislation and the effect seismic surveys can have on marine life.

2.1 Seismic survey sound

In general, underwater sound can be split into two categories: continuous and impulsive sound. The sound produced during seismic surveys is classified as impulsive sound. Pile driving for offshore wind farms is another example of impulsive sound. Whereas in the case of pile driving the sound that is generated is an unwanted side effect. In the case of seismic surveys, the sound produced is the desirable effect. This difference has important implications for the possibilities to combat the negative effects with regulation and legislation.

2.1.1 Sound source characteristics

To generate sound waves for surveys a seismic source is deployed. The purpose of this source is to generate low frequency sound pulses with the required strength, duration and frequency range. However, there are also high levels of higher frequencies generated. The seismic source for 2D, 3D and 4D surveys (see Annex A2) are almost always made up of sub-arrays or single strings of multiple airguns. The purpose of the airgun arrays is to produce high-energy, low-frequency sound in the form of sharp, short-duration pulses. Airgun arrays are designed to direct a large proportion of the sound energy downwards. Despite this downward focusing effect of the array, relatively strong sound pulses will propagate in all directions. The output of the seismic source depends on various variables:

1 The output of an airgun is directly proportional to the operating pressure of the airgun (generally expressed in pounds per square inch [psi]);

2 The output of an airgun increases as the cube root of the volume (the volume is expressed in cu inch);

3 The output of an airgun array is generally directly proportional to the number of airguns in the array;

4 Airgun arrays are not point sources; they typically have dimensions of 15 – 30 metres by 15 – 20 metres;

5 The actual maximum sound output of an array is less than the modelled value, typically some 15 to 25 dB less. This discrepancy in values is caused by the distribution of the airguns in an array and is commonly referred to as the ‘array effect’;

6 The primary output of an airgun source typically has most of the energy in the bandwidth range between 10 and 200 Hz. This bandwidth is of the most interest for seismic surveys. However, some energy will be present up to 500 - 1000 Hz. Each array type has its own signature with respect to the amplitude and frequency pattern.

7 The airgun is fired at predetermined intervals, generally every 10 to 12 seconds, depending on vessel speed.

Based upon data from the interviews, in the previous decades airgun arrays up to 4600 cu inch were used. Nowadays the airguns used on the DCS are around a maximum of 3400 cu inch, which give a peak to peak output of around 100 bar-m. This volume may be somewhat oversized for the North Sea depending on the area. Airguns from 1000 cu inch or smaller have appeared to be deficient in low frequencies which are needed for some processes.

2.1.2 Noise frequencies and sound levels

The primary output of an airgun source typically has most of the energy in the frequency bandwidth between 10 and 200 Hz, which is the frequency bandwidth of most interest in seismic surveying. However, airguns also yield higher frequencies. These higher frequencies are usually not useful for geologists, as they do not contribute to the seismic imaging and because higher frequencies mute faster than lower frequencies. Figure 2-1 gives an impression of the frequency distribution of a typical airgun array used in seismic surveys. The capricious pattern of the frequency distribution is inter alia, because an array is composed of several airguns which are tuned in such a way that the signal of the individual airguns is increased in certain directions and frequency, while in others the individual contribution is cancelled. Besides the strengthening and cancelling of the signal is caused by the upward part of the signal that is bounced back from the sea surface and thereafter interferes with the original pulse. The frequency distribution in Figure 2-1 can be compared with the audiograms of sea mammals and of fish (for an elaboration see section 2.2.1 and for more information Annex A1), which show that in general sea mammals are relatively sensitive for the higher frequencies of seismic sound and less sensitive to the lower frequencies of seismic sound. However, based on the audiograms of cod, herring and sol (50 – 1000 Hz; Annex 1), fish have an overlap with the lower frequencies of seismic sound, with most of the energy in the frequency bandwidth between 10 and 200 Hz. Hence, for sea mammals minimizing acoustic energy at higher frequencies is desirable from a geological imaging perspective and to reduce concerns about marine species such as the harbour porpoise or harbour seal, which use high-frequency sound. For the fish this would mean minimizing the acoustic energy at lower frequencies. This is not possible as the low frequencies are essential for the geological imaging of the seabed.

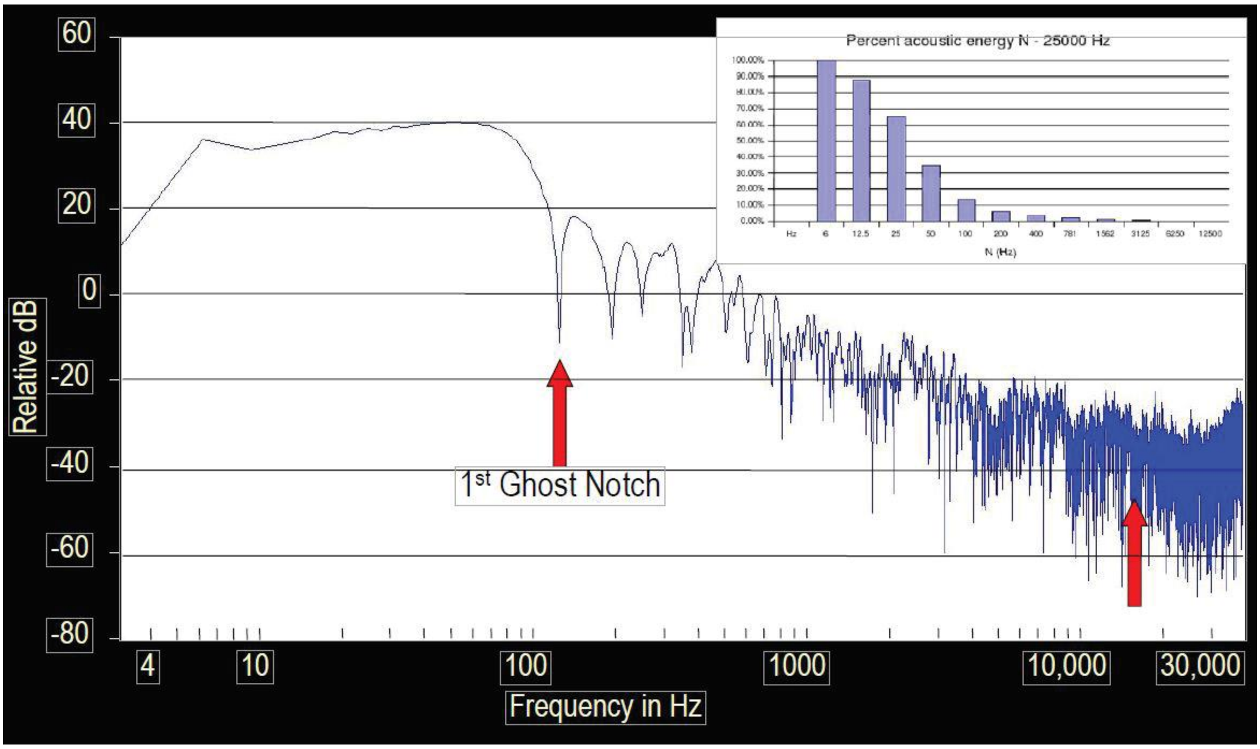

Figure 2-1 Frequency-transformed distribution of acoustic energy in a typical seismic array pulse. Inset (top right): percentage of energy in each frequency band, which can be useful to readers unfamiliar with the logarithmic expressions of pressure and frequency used in acoustics. Note the effects of the "ghost notch"[1] at 125 Hz and multiples thereof. (source Acoustics Today volume 12, issue 4, Winter 2016, Robert C. Gisiner, Graphic provided by Schlumberger Ltd).

2.2 Scoping Ecological Effects

More details on the available information of the underwater noise effects on marine species is included in Annex A1. Below only the essential parts for this CBA are presented.

Sound travels fast in the sea and has good propagation abilities, which makes it an excellent means of rapid information acquisition and exchange. Many marine animals have therefore developed auditory capabilities and rely on the sound to overcome the many challenges of living in the sea. However, in recent times the world seas have become noisier altering the quality of the marine environment with consequences on physiology, communication, behaviour and energetics of different marine species (Rako-Gospić & Picciulin, 2019).

The mechanism of sound perception and the way sound (physically) effects marine life varies from species to species. The effects of noise can coarsely be divided into physical and non-physical effects. Physical effects include mortality, shift in hearing thresholds (either permanent or temporary) and damage to body tissue. Non-physical effects include: indirect effects such as reduced prey availability, chronic effects such as stress, behavioural effects e.g. avoidance of an area, changes in dive and respiratory patterns, disruption of feeding and perceptual effects e.g. masking of biologically significant noises by man-made noise (including an animal's communication signals, echolocation, and sounds associated with finding prey or avoiding predators or human threats such as shipping) (van der Graaf *et al.*, 2012). Physical effects caused by sound

[1] A ghost notch arises because of the "ghost" effect and is thus referred to as the "ghost notch". Energy travels up from the sound source and is reflected off the sea surface. When this energy combines with the original down-traveling energy, the waveshape is changed and the "ghost" is created.

exposure usually occur only at very high noise energy levels and close to the sound source, while the non-physical effects can occur at lower noise levels and sometimes even at great distances from the sound source.

2.2.1 Impact of seismic surveys on marine animals

To determine the effects of seismic sound on marine life on the DCS, information is required of the hearing thresholds, behavioural change and population impact of the different species (groups). Recently an analysis was performed on the data availability and suitability for the species in the North Sea. This analysis is part of the recently published report on ‘Assessment Methodology for Impulse Noise’ (Versteeg et al., 2020). In this report an overview is given of the North Sea fauna and which species could be used to assess the impact of impulse noise on the marine environment in the North Sea. The goal was to select indicator species to assess and monitor the effects of impulsive noise including seismic sound sources. The selection of the species was based on multiple variables such as data availability and suitability, spatio-temporal distribution and protection status on national and international level. It was concluded that Atlantic cod, harbour seal and harbour porpoise are suitable as indicator species for impulse noise. Additionally, these three species together cover a large part of the frequency ranges caused by seismic sound. Atlantic cod is sensitive for the lower frequencies, the harbour seal and the harbour porpoise for the higher frequencies. Therefore, this report will only take these species into consideration with regard to noise caused by seismic survey activities. This does not mean that other marine organisms are not susceptible to impulse noise by seismic surveys activities. It is well known that also other marine organisms are susceptible to sound such as zooplankton, bivalves, crustaceans, echinoderms, cephalopods etc (Carroll *et al*., 2017). However, not enough data is available to come to a sound conclusion on what the extent of these effects are.

One of the most widely recognized physical effects of exposure to impulsive sound is a noise-induced threshold shift—an elevation of hearing thresholds following cessation of the noise. These include Temporary Threshold Shift (TTS) and Permanent Threshold shift (PTS). TTS is a temporary shift in the auditory threshold, where the hearing eventually returns to normal. The threshold shift may occur suddenly after exposure to high noise levels. If the hearing threshold does not return to normal it is called PTS (Finneran, 2015). In Table 2-1 an overview is given of the hearing thresholds where non-physical and physical effects start to occur.

Table 2-1 Calculated threshold values that have a certain impact on harbour porpoises, harbour seals and fish. Sound exposure level (SEL) is proportional to the total energy of a signal expressed in dB re 1 µPa2 s. Source Southall, 2007. SEL1 = noise level of one single strike; SELcum = noise level perceived by a marine mammal after pile driving activity of one pile thus multiple strikes; SEL1 + cum,w = M-weighted SEL for seals in water, see Southal et al. (2019)

Species	Type of effect	Threshold value	Literature
Harbour porpoise	Avoidance	SEL_1 > 140 dB re 1 µPa^2s/ 136 dB re 1 µPa^2s	(Kastelein et al., 2011)
	TTS-onset	SEL_{cum} > 164 dB re 1 µPa^2s	(Lucke et al., 2009)
	TTS-1 hour	SEL_{cum} > 169 dB re 1 µPa^2s	TTS-onset + 5 dB
	PTS-onset	SEL_{cum} > 170 dB re 1 µPa^2s	TTS-onset + 15 dB
Harbour seal	Avoidance	$SEL_{1,w}$ > 145 dB re 1 µPa^2s	(Kastelein et al., 2011)
	TTS-onset	$SEL_{cum,w}$ > 171 dB re 1 µPa^2s	PTS-onset – 15 dB
	TTS-1 hour	$SEL_{cum,w}$ > 176 dB re 1 µPa^2s	TTS-onset + 5 dB

	PTS-onset	$SEL_{cum,w}$ > 186 dB re 1 μPa^2s	(Southall et al., 2019)
Large Fish*	TTS-onset	SEL > 187 dB re 1 μPa^2s	(Oestman et al., 2009)
Small Fish (< 2 gram)*	TTS-onset	SEL > 183 dB re 1 μPa^2s	(Oestman et al., 2009)

*research shows that fish are less sensitive to underwater noise then Oestman *et al.* (2009) suggested (Halvorsen *et al.,* 2012a; Halvorsen *et al*., 2012b).

Direct physical damage by impulsive sound activities is mitigated by applying an Acoustic Deterrent Device (ADD) and a soft start, which deters the marine animals and prevents permanent damage. This is a prerequisite mitigation measure for all activities on the DCS when noise-induced hearing thresholds are exceeded. This applies to seismic surveys as well as for other activities, such as pile driving for wind farms.

Harbour porpoise

Most research in relation to underwater sound is focused on the harbour porpoise and bottlenose dolphin. For this study the harbour porpoise is relevant as this marine mammal is the most abundant in the Dutch North Sea. The harbour porpoise is legally protected by the Dutch Nature Protection Act. Seismic surveys have been deployed for decades and up until now there is no scientific proof that this activity has had a significant negative impact on the harbour porpoise population. In the studies of IJsseldijk *et al.* (2019;2020) a sharp increase was seen in harbour porpoise strandings between 2011 and 2013. Whether there is a correlation between anthropogenic activities and the strandings has not yet been researched. Over the past year an increase has been observed in the harbour porpoise population, which led to categorize the conservation status for this species as 'good'. Even though an increase is seen in the population abundance in the Dutch North Sea, it does not mean the population is actually growing. Researchers have argued that this species population is shifting from the Northern North Sea to the Southern North Sea (Ecosystemen, 2017).

The noise characteristics of seismic sound in relation to the audio spectrum from the harbour porpoise (Annex A1) show that it is unlikely that hearing damage will occur at higher frequencies, however the possibility of hearing damage cannot be entirely neglected. Kastelein *et al.* (2015) showed that the sound energy levels in the lower frequencies (500-800 Hz) can cause reduced hearing at higher frequencies in harbour porpoise. Additionally, multiple studies have proven that non-physical damage (e.g. behavioural change) occurs at great distances from the seismic sound source. Recently a study was published by Sarnocińska et al. (2020) which gives insight into the reaction of the harbour porpoise to a 3D seismic airgun survey in the Danish North Sea. During the seismic survey a decrease in echolocation was observed. The presence of harbour porpoise by foraging buzzes and social calls, were observed up to 8 – 12 km away from the vessel. The researchers concluded that this suggests that the density of porpoises is reduced within a radius of 8 – 12 km around the moving seismic vessel (Sarnocińska *et al.*, 2020).

Harbour seal

The harbour seal is widely distributed along the coast of the Dutch North Sea and legally protected by the Dutch Nature Protection Act. Over the last decade the harbour seal population has increased in the Dutch North Sea, implying that the population is doing well. Therefore, the conservation status of the harbour seal is categorized as 'good'.

Harbour seals primarily use vocalisations for communication, mainly in the context of territorial and reproductive behaviour. The seals hearing is most sensitive between the frequencies of 8 and 16 kHz (Annex A1). It is known that the harbour seal shows a strong avoidance reaction (and stops feeding) in areas exposed to sound levels of 145 dB re 1 μPa^2 s (Thompson *et al.,* 2019). This threshold value is also used in the 'Kader Ecologie en Cumulatie' (KEC). The KEC focuses on possible cumulative effects on the populations of species to be protected during the construction and operation of offshore wind farms (for more information see section 2.3.2). When comparing the noise from seismic surveys to the noise sensitivity of harbour seals it can be concluded that when harbour seals are in the proximity of the seismic sound source, physical damage is likely to occur. At larger distances multiple non-physical effects can occur resulting in a lower energy intake which could have a negative effect on the population, especially when the individuals are exposed to the sound for longer periods of time. However, with the current knowledge the actual population-effect cannot be quantified yet. Additionally, the current available population models do not contain the parameters to assess the effects of seismic activities on population level. More research need to be done one dosis-effect relations, which in turn can provide input for the populations models (pers. comm. R. Kasteleijn and F. Heinis).

Atlantic cod

The commercially important Atlantic cod is a hearing specialist, which makes this species sensitive to sound. This species in not legally protected under the Dutch Nature Protection Act. Several studies on the effects of seismic surveys found a reduction in catch rates of cod and other fish species (Bohne et al., 1985; Skalski et al., 1992; Engås *et al,* 1996; Løkkeborg et al., 2012b, 2012a). Another study showed that when cod was exposed to pure tones (50 Hz to 400 Hz at 180 dB) for 1 to 5 hours, this led to physical injury (Enger 1981). Additionally, Sierra-Flores *et al.*, (2015) showed that impulse sound induced a behavioural response and a stress response which led to a disturbance in reproductive success. Recently a paper was published by Soudijn *et al.* on population-level effects of acoustic disturbance in Atlantic cod. The study suggests that through increased stress, changes in foraging and movement behaviour, and effects on the auditory system, anthropogenic noise can lead to increased energy expenditure, reduced food intake, increased mortality and reduced reproductive output. Sub-lethal effects of sound exposure may thus affect populations of cod more than lethal effects of sound exposure (Soudijn *et al.*, 2020).

> The North Sea fauna comprises out of benthos, zooplankton, nekton and seabirds. Benthos include the communities of organisms that live on or in the seabed and comprise out of invertebrate species, excluding fish. Zooplankton includes a wide range of taxonomic groups of mostly small animals (invertebrates, chordates and fish larvae) that drift or weakly swim, primarily near the surface. Nekton comprises of organisms that can actively swim and move independently of water currents such as cephalopods (squid and octopus), bony fish, elasmobranchs (sharks and rays) and marine mammals. Research indicates that all of these taxonomic groups include species which are vulnerable to sound, however the extent of the effects is not well understood.

2.2.2 Challenges in sound calculations in relation to disturbance

There are two main challenges when calculating the impact of noise from seismic explorations. The first being the calculation of the noise profile from the sound source, in this case the airgun arrays. Secondly, the calculation of sound propagation through the water column, which is based on the noise profile.

There are multiple source models available that calculate the source sound from airgun arrays. These models are however mainly focussed on the lower frequencies as these frequencies are the most important for the seismic acquisition. Recent findings suggest that the models are underestimating the energy levels in the higher frequency ranges. An international research project is working towards a better understanding of the noise in the higher frequency ranges. Currently it can be assumed that the higher frequencies are underestimated in the available sound propagation models, which means that high frequency sensitive marine species can be detrimentally affected (Interview with TNO, 2020).

In the study “Inventory and assessment of models and methods used for describing, quantifying and assessing cumulative effects of offshore wind farms” (van Oostveen et al., 2018) an overview is given of noise propagation models for underwater noise with their pros and cons. These models are mainly used and calibrated towards offshore piling. Recent field measurements suggest that the broadband sound propagation calculated by these models for seismic arrays are not in line with each other and can result in a large underestimation as well as a large overestimation. The current theory is that the shallow geological structures under the seabed (about the first 100 m below the seabed) can have a major effect on the propagation of sound, mainly in the lower frequency ranges. These geological structures are however not part of the model parameters of the current available models (Interview with TNO, 2020). In the North Sea Agreement multiple research projects have been proposed to gain more insight into the impact of seismic surveys on the marine environment. The outcome of these research projects could aid in the advancement and improvement the available models.

In summary this means that the current available sound propagation models cannot concisely predict the sound propagation of airguns under water, which leads to difficulties in determining the effect of seismic surveys on marine animals.

Broadband versus frequency weighing
As the discussed species have a hearing range of only a part of the sound spectrum produced by the seismic sources and the main weight of the noise from seismic exploration is within the lower frequencies, frequency weighing can give better insight in the disturbance of specific species (Southall, 2019). With frequency weighing only the frequencies animals can actually hear are being assessed. This does however ask for detailed noise source and noise propagation calculations per species, which is currently not available. Under Offshore wind energy ecological programme (WOZEP) a study on frequency weighting is being conducted.

2.3 Policy and regulation

Many countries have guidelines in place for the regulation of seismic surveys and/or activities which produce impulsive sound. An overview of the different policies and regulations related to this topic is given in the paragraphs below. The purpose of this overview is to gain a better understanding of the different policy and regulation options for seismic surveys on the DCS.

2.3.1 International regulation/standards

International guidelines by the International Association of Oil & Gas Producers (IOGP)
Many international Oil & Gas companies follow the international guidelines set by IOGP. According to the IOGP the measures mentioned in the ‘Recommended monitoring and mitigation measures for cetaceans during marine seismic survey geophysical operations’ report are recommended for use during all marine seismic surveys that use compressed air source arrays. These recommendations include implementing an exclusion zone of 500 meters, which should be observed for at least 30 minutes prior to the seismic source being activated by a Marine Mammal Observer (MMO) or Passive Acoustic Monitoring device (PAM). The seismic survey should start with a so called soft-start procedure, whereby the source level is increased gradually before use at full power. During periods of poor visibility, a PAM is recommended to use. The monitoring data should be made available externally within a reasonable time frame of completing the seismic survey activity. If the seismic sources are silent for 20 minutes or more, the soft-start should be used again before re-initiating operations (Sound of Marine Life, 2020).

International legislation by country
Erbe (2013) gives an overview of international regulation on underwater noise. The following paragraphs provide examples of underwater noise regulation in different countries. Specific regulation on seismic survey

is limited and is usually based on regulation for windfarm construction. While specific requirements differ from country to country, the general elements in the various regulations are largely similar and may involve:

- The source – source used with minimal practical power.
- Location & Timing – mostly applied to seismic surveys.
- Operational parameters – Soft-start/ramp-up when starting the seismic survey
- Mitigation Equipment – mainly applied to pile driving activities such as the use of bubble screens
- Mitigation Procedures – safety zones, MMO, pre-shoot survey, low-power and shut down and PAM

United Kingdom

The Joint Nature Conservation Committee (JNCC) released a seismic survey guideline protocol for minimising the risk of injury to marine mammals (JNCC, 2017). The developer must determine what species are present when and consider seasonal timing. The Best Available Technique (BAT) has to be employed within the constraints of commercial affordability and practicality. Simultaneous visual and PAM is suggested during operations. There are requirements for MMO and PAM operators' training and work schedules, location (viewing platform) and equipment. The size of the monitoring and mitigation zones is established during the environmental impact assessment and agreed with the regulator. PAM should be used during periods when visual mitigation is not possible. Pre-shooting surveys and soft-start should be incorporated into the survey design.

Germany

The German Federal Government requires an exclusion zone of 750 m from pile driving for marine mammals. Measures must be employed by the operator to keep the received level at 750 m below a sound exposure value of 160 dB re 1 µPa2s and below a peak-to-peak sound pressure value of 190 dB re 1 µPa. Temporal and spatial restrictions are additionally considered in critical habitats during seasons of high animal abundance. Underwater sound produced by seismic surveys abide by these same set of requirements (Erbe, 2013).

United States of America

The Endangered Species Act (ESA) protects endangered species across the classes (including marine mammals). The National Marine Sanctuaries Act protects marine environments with special national significance. The Marine Mammal Protection Act (MMPA) specifically protects marine mammals from anthropogenic noise. It is administered by the National Marine Fisheries Service (NMFS) and the Fish and Wildlife Service. NMFS has taken the more active role in issues related to underwater noise.

The MMPA defines 'take' as harassment, hunting, capture, killing or collection - or the attempt thereof. Under the 1994 Amendments to the MMPA, harassment is defined as any act of pursuit, torment or annoyance, that has the potential to injure (Level A Harassment) or to disturb (Level B Harassment) a marine mammal or stock in the wild.

NMFS' policy for pulsed sound is currently under review and requires that cetaceans and pinnipeds will not be exposed to SPLrms > 180 and 190 dB re 1 µPa respectively, to prevent Level A Harassment. The threshold for Level B Harassment from pulsed sound is generally set at 160 dB re 1 µPa rms.

New Zealand

In 2012 the Department of Conservation developed a voluntary Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations following discussions with international and domestic stakeholders representing industry, observers and marine scientists (Seismic survey code of conduct, 2020). The Code has been endorsed as industry best practice by the Petroleum Exploration and Production Association of New Zealand (PEPANZ).

The code categorises seismic surveys in three levels:

- Level 1 (source > 427 in3): minimum of 2 MMOs and 2 PAM operators present at all times; pre-operation MMO and PAM survey of 30 minutes over mitigation zone; 20- 40 minute soft-start; 1.5 km shut-down zone for Species of Concern with calves; 1 km shut-down zone for Species of Concern without calves; delayed start if Other Marine Mammal within 200 meter
- Level 2 (source 151-426 in3): minimum of 2 MMOs present at all times; PAM optional; pre-operation MMO survey of 30 minutes over mitigation zone; 20-40 min soft-start; 1 km shut-down zone for Species of Concern with calves; 600 m shut-down zone for Species of Concern without calves; delayed start if Other Marine Mammal within 200 meter
- Level 3 (source < 150 in3, sparkers, pingers, boomers): no specific mitigation zones

Detailed requirements for the training and experience of MMO or PAM are described in the Code of Conduct. While the code explicitly treats marine mammals, operators are strongly encouraged to consider and mitigate impacts on other key species.

Australia

The operator must develop an environment plan (EP) for assessment and acceptance by the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) prior to operations. The intent of the EP is to act not only as a regulatory compliance document, but also as a practical implementation and management tool to be used by operators in the field. The EP will describe the operations in enough detail to determine potential environmental risks and impacts. The EP will further describe the natural physical and biological environment, including any environmental receptors that may be affected by the proposed operations (both planned and unplanned), and spatio-temporal sensitivities (e.g. breeding and nesting seasons and habitats, animal migrations, spawning events). The EPBC Act Policy Statement 2.1 (2008)[2], provides standards and a framework designed to minimise the risk of acoustic impacts to whales (baleen whales and large toothed whales) from marine seismic operations. Seismic surveys should be planned outside of whale breeding, calving, resting or feeding habitats and times. Thirty-minute pre-operation visual observation, 30-minute soft-start, start-up delay if whales are sighted within the low-power zone, ongoing visual observation during operations, and power-down or shut-down if a whale is sighted within the low-power or shut-down zone are required irrespective of location and time of year of survey. Passive acoustic monitoring is recommended in addition to visual observation, specifically during low visibility. This policy statement requires the computation of the SEL from single emissions at 1 km range. If SEL > 160 dB re 1 µPa2s for 95% of the time, an observation zone of 3 km, a low-power zone of 2 km and a shut-down zone of 500 m are imposed. Else, these zones are 3 km, 1 km and 500 m respectively.

2.3.2 Current policy and regulation in NL

In this study we focus on the acts, policies and agreements that are relevant for the CBA. These include the Dutch Nature Protection Act (Wet Natuurbescherming), North Sea Agreement, Framework for Assessing Ecological and Cumulative Effects (KEC), Harbour Porpoise Conservation Plan and Small Field Policy. More detailed information is given below. Other regulations are not or only in general considered because these regulations contain no conditions that are relevant for the CBA. The Mining Act and Water Act indeed contain articles concerning the execution of seismic surveys, but these articles are only related to the execution of the surveys and not to the protection of species.

[2] https://www.environment.gov.au/system/files/resources/8d928995-0694-414e-a082-0ea1fff62fc8/files/seismic-whales.pdf

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Dutch Nature protection Act

The ecological requirements are laid down in the Dutch Nature Protection Act (Wet Natuurbescherming). Species and habitats are protected through the EU directives 92/43/EEC (Habitats Directive) and 2009/147/EC (Birds Directive). These Directives are implemented in the Dutch legislation through the Dutch Nature Protection Act. The Act is split into three main parts: Protection of species, protection of habitats, and the protection of forests. Of those parts, the protection of species and habitats is most relevant for activities on the Dutch Exclusive Economic Zone. For any human activity that possibly has a (significant) negative impact on the marine protected species or marine protected habitats an exemption and or permit is required under the Dutch Nature Protection Act.

A noise budget in any form does not exclude a future project from the conservation objectives of the protected areas and species.

North Sea Agreement

The North Sea Agreement describes several agreements regarding seismic surveys by government, industry and NGO's. Seismic surveying will be done, as much as possible, outside of the harbour porpoise reproductive season which lasts from the 1st of May until the 1st of September. The use of e-source airguns will be implemented when possible. Any decision to acquire seismic data should be based on specific survey requirements, potential survey designs and their associated risks. Also, a transparent research programme will be set up, including all the stakeholders involved throughout the process. This programme will investigate how to minimise sound levels of 3D seismic surveys, whilst yielding the necessary results, based on the Best Available Techniques and within the legal framework. As a result, the amount of excessive levels entering the ecosystem will be reduced.

Framework for Assessing Ecological and Cumulative Effects (KEC)[3]

The Framework for Assessing Ecological and Cumulative Effects focuses on possible cumulative effects on the populations of species to be protected during the construction and operation of offshore wind farms in the period leading up to 2030. For the harbour porpoises, it was decided to assess the effects on population level, whereby a maximum reduction of 5% of the current population is accepted due to the construction of offshore wind farms. In the KEC the calculation of the effects of underwater sound on harbour porpoises is based on activities from the offshore wind energy sectors. Seismic surveys were not included because one could argue that this sound, resulting from oil and gas prospecting, has been present for many years. Given the decision to adopt population dynamics parameters, this factor has already been taken into account implicitly in the Interim Population Consequences of Disturbance (iPCoD) model. This model allows the user to predict the population consequences of disturbance and/or injury that may result from offshore energy developments.

Harbour Porpoise Conservation Plan

The Harbour Porpoise Conservation Plan focuses on what is needed to fulfil the legal requirements from the perspective of policy and management with the overall aim to maintain a Favourable Conservation Status of the species in the Dutch waters. Regarding seismic surveying, more elaborated efforts to investigate and assess the impact of this activity are recommended, in collaboration with the industry. Here the plan refers to the planned research in the North Sea Agreement where research will be conducted to determine the amount of sound needed to achieve the objective of a survey and minimize the amount (and the frequency band) of sound sent into the water column. In this plan a framework similar to the KEC is proposed.

[3] https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/ecology/accumulation-ecological-effects/framework-assessing-ecological-cumulative-effects/

Small Fields Policy
Since the oil crisis in the 1970s, the Dutch government has promoted the exploration and production of small gas fields in the Netherlands, both onshore and offshore. Fiscal measures have been put in place and offtake (purchase) of the gas is guaranteed by GasTerra[4] (Gasunie before 2005). Recently, it has been decided that no more exploration licences will be issued for the exploitation of onshore gas as well as for shale gas[1]. Offshore gas fields are now the only new reservoirs which can still be explored and produced.

While the Dutch government policy is to gradually phase out the use of natural gas until the energy system is carbon neutral in 2050, natural gas is expected to remain of importance for the security and diversification of energy supply. With the largest gas field in The Netherlands, Groningen, producing less than before and scheduled to stop producing entirely after 2022, small gas fields make an important contribution to the energy system. Alternatives, such as the import of natural gas from Russia or as LNG, will lead to higher upstream carbon emissions. Also, the security of supply and impact on the economy of gas from small fields in The Netherlands is more beneficial. For those reasons, the Dutch government prefers gas from small fields over imported gas[5].

2.3.3 Mitigating measures

To mitigate negative effects of seismic survey on marine life various mitigating measures can be deployed and are usually standard practice:

- Avoidance of important feeding and breeding areas, either on a permanent basis, or seasonally avoiding operations in sensitive seasons;
- Deploying MMOs or protected species observers (PSOs). The MMO observes visually the presence of marine mammals near the survey vessel, possibly aided by hydrophones (PAM) to detect and localise vocalising marine mammals. When the MMO observes protected species the start of the seismic activities should be delayed until the animals have left the area;
- Use of ADD to discourage marine mammals from approaching an area where man-made sound may cause impacts to marine mammals. Such ADDs can aid in the dispelling of animals out of the vicinity of the survey vessel;
- Soft start (gradual ramping up of a seismic sound source) in order to give sea mammals and fish the opportunity to leave the area before they may encounter auditory injuries from the underwater sound of the airguns;
- Optimised design of the airgun array to avoid the use of larger airgun arrays than required for a certain survey e.g. no use of overrated arrays.

Next to the above proven techniques, tests have also been conducted to apply bubble screens around the airgun arrays to shield the lateral high frequency noise propagation from the airguns. Also, other means have been tested to shield lateral noise propagation and/or to focus airgun energy downward.

None of the above mitigating measures are prescribed in legislation, nor directly or indirectly mandatory, by setting standards for the impact on species. However, certain measures can be enforced by setting conditions in the Nature Permit, that should be applied for by the operator. Measures can also be enforced based on the direct action of article 6 of the Habitat Directive. In this article it is stated that Member states shall

[4] In September 2020 the Minister of economic affairs informed Parliament of the termination plan of GasTerra. This also includes a proposal to cancel the obligation regarding the small fields. (Kamerbrief, Afbouwplan GasTerra, 24 Sept. 2020)
[5] Letter from Minster of Economic Affairs to Parliament May 30th 2018, "Gaswinning uit de kleine velden in de energietransitie"

take appropriate steps to avoid the disturbances of the species for which the areas have been designated, in so far as such disturbance could be significant in relation to the objectives of this directive.

Although not prescribed in legislation, in practice, the use of soft starts, ADDs and marine mammal observers is an obligation to be able to get a nature permit for activities with high levels of (impulsive) underwater noise on the DCS.

2.4 Conclusion

Based on the above, we can conclude that sound from seismic exploration can physically harm animals that are sensitive for the lower frequencies as well as the higher frequencies and can potentially have an effect on population levels because of (indirect) non-physical effects. We can also conclude that with the use of commonly used mitigation measures that will scare the animals away, direct physical harm is likely to be negligible on (fast) moving animals like marine mammals and pelagic fish. The effect on other organisms, that cannot escape the noise, is largely unknown. The other (indirect physical) effects of sound on marine animals e.g. impacts related to reduced energy intake, cannot be mitigated by the commonly used mitigation measures that are practiced in the North Sea. This possible population effect can occur by species sensitive to the lower frequencies (fishes) as well as the higher frequencies (marine mammals). However, for none of the animals a system is in place to quantify the exact impacts e.g. on population level. There are population models available for the harbour porpoise based on disturbance, but the data derived for these models is mainly based on noise from piling of offshore wind foundations and not based on seismic sound sources. At this moment, there are no population models related to noise disturbance available for other species .

There is already regulation in place that aims to reduce potential ecological impacts of large scale offshore seismic surveys: As part of the Dutch Nature Conservation Law an ecological impact assessment must be performed. If (significant) impacts are expected, the initiator will have to apply for a nature conservation permit at the Ministry of Agriculture, Nature and Food Quality (protected areas) and/or the Netherlands Enterprise Agency (protected species). The competent authorities will assess per application whether the impacts are acceptable. In addition, mitigation measures need to be taken to reduce the impacts.

3 Seismic surveys: reference scenario

This chapter describes the current activities and future prospective of seismic surveys and provides a preliminary ecological assessment of the reference scenario. The reference scenario (or baseline alternative) is the current situation of seismic surveys on the DCS and the expected development if no additional measures are taken. In accordance with common theory and practice for Cost Benefit Analysis, the reference scenario is not equal to “doing nothing”. Even in the absence of additional measures, seismic surveying is subject to existing agreements, policy and regulation.

3.1 Current seismic surveys techniques

This section gives a short overview of the techniques currently used for seismic surveys on the DCS. For a more detailed description of the techniques we refer the reader to Annex A2.

Towed streamer data acquisition
All seismic surveys involve a source to generate sound waves and some configuration of receivers or sensors to record the reflected sound waves. With towed streamers the hydrophones are placed in streamers (a cable containing the hydrophone) which are towed or ‘streamed’ behind a moving survey vessel. These

streamers are typically 3 to 8 kilometres long. For 2D surveys generally one airgun array and one streamer are deployed, for 3D surveys generally two airgun arrays and multiple streamers (6 - 8) are deployed. For 3D surveys, the area of interest is investigated by sailing parallel sail lines to obtain a three-dimensional view of the subsurface. The sail lines are normally 400 to 800 meters apart from each other. Other patterns are also possible.

Ocean bottom seismic techniques

At ocean bottom seismic techniques also sound waves are produced by a vessel that tows airgun arrays through the water. However, the sensors to record the reflected sound waves are not located in streamers but lay on the seafloor or may even be buried in the top layer of the seabed. The advantage of ocean bottom techniques is that the data is more detailed and of better quality. Based on data from an interview, ocean bottom seismic techniques, such as Ocean Bottom Nodes (OBN), surveys are more time consuming and expensive. However, this highly depends on the survey design. As a very general rule of thumb (dependent on the scope of the survey), OBN surveys can be 6 to 8 times more expensive than SDS. However, OBN surveys can also yield more geological information.

Bandwidth-Controlled Seismic Source

The industry has developed Bandwidth-Controlled Seismic Sound Sources. An example is the “eSource”, a product of Teledyne Bolt[6]. The eSource was developed with the aim to minimize sound level of the high frequency components for which the cetaceans are most sensitive, while maintaining the optimal band-width for subsurface imaging.

3.2 Emerging seismic survey techniques

This section gives a brief overview of an emerging seismic survey technique which is still in development and not yet commercially used.

Marine vibroseis[7]

While airgun arrays produce impulsive soundwaves with a high energy content, marine vibroseis produces sound waves of a long duration and a lower energy level. Therefore, the environmental effects will be different, but are still largely unknown. Marine vibroseis has existed already for many years as an alternative for airguns but has not yet resulted in a commercially and technologically viable system that can compete with the signal quality and reliability of air guns. Because of the environmental impact of airguns, but also to overcome technological disadvantages of airguns (repeatability of the seismic signal and control of its frequency content), the industry is working on the further development of marine vibroseis.

3.3 Seismic surveys in the North Sea – past, current and future

Since the beginning of the 1960’s, a large part of the DCS is mapped by seismic surveys. Initially by 2D surveys but since 1981 also with 3D surveys. Figure 3-1 shows the acquired 3D seismic survey area at the DCS in the period 1963 – 2019. In the eighties an average of 1000 km^2 per year was surveyed, in the nineties on average 3300 km^2 per year, in the zeros on average 1400 km^2 per year and in the past decade 1200 km^2 per year.

As a result, a large part of the Dutch North Sea is by now mapped with 3D surveys. As can be seen in Figure 3-2, there are only some blank spots left. A comment must be made here, that the quality of the early surveys is not as good as the quality that can be acquired with the current techniques. To be able to reuse

[6] *http://www.teledynemarine.com/eSource?ProductLineID=70*
[7] *https://www.ep.total.com/en/innovations/research-development/marine-vibrator-optimizing-seismic-acquisitions*
https://www.tandfonline.com/doi/pdf/10.1071/ASEG2018abW9_2A?needAccess=true
file:///C:/Users/nl68901/Downloads/MasterThesis.pdf

the early data, the data should be reprocessed and, in some cases, it might be necessary to acquire new data from new seismic surveys. Energie Beheer Nederland (EBN)[8], mentions in her outlook for the energy transition[9] that they want to map the blank spots on the 3D map. It is EBN's ambition to identify all economically recoverable oil and gas fields offshore before 2025. This would mean that the intended 3D data acquisition should take place in the coming years.
However, based on the interviews with the offshore Energy and Petrol (E&P) industry, NOGEPA and EBN it appeared that with current insights the industry has plans to carry out a limited number of 3D surveys, with an average surface area of 4600 km^2 in total, see Figure 3-3. When and if these seismic surveys will take place is not clear and depends greatly on the economic situation. These surveys do not include possible seismic surveys needed for CCS (Carbon Capture and Storage). It is of yet unclear if seismic surveys are needed to facilitate CCS in underground reservoirs and, if so, what the extent of these surveys will be.

It is hard to forecast the area that will be surveyed in the coming years, as this highly depends on the oil and gas prices and the economic climate. Also, the energy policy of the Dutch government with regard to the exploration and production from small fields onshore and offshore plays an important role. This includes possible stimulation measures, such as tax reductions.

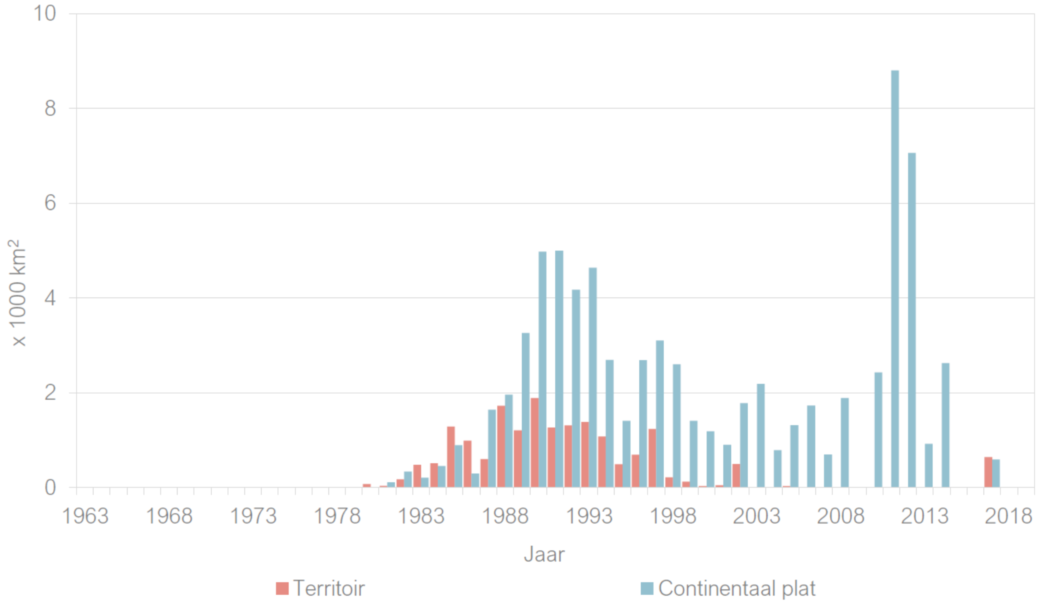

Figure 3-1: Acquired 3D seismic survey area at the DCS in the period 1963 – 2019 (Jaarverslag 2019 Delfstoffen en Aardwarmte, Ministry of Economic Affairs, 2020).

[8] *EBN is a natural gas exploration, production, transportation and sale company owned by the Dutch Government and is involved in most offshore activities concerning oil and gas.*
[9] *FOCUS Energie in beweging, EBN 2018*

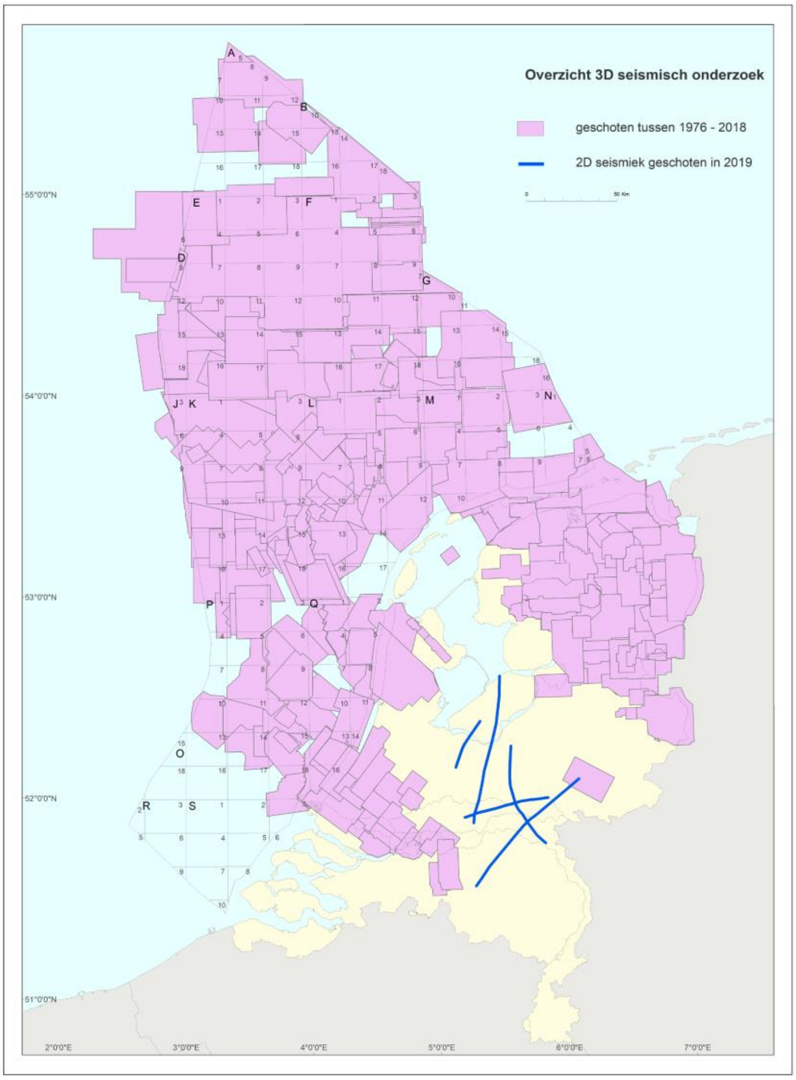

Figure 3-2: Overview of 3D seismic surveyed area at 1st of January 2020 (Jaarverslag 2019 Delfstoffen en Aardwarmte, Ministry of Economic Affairs, 2020).

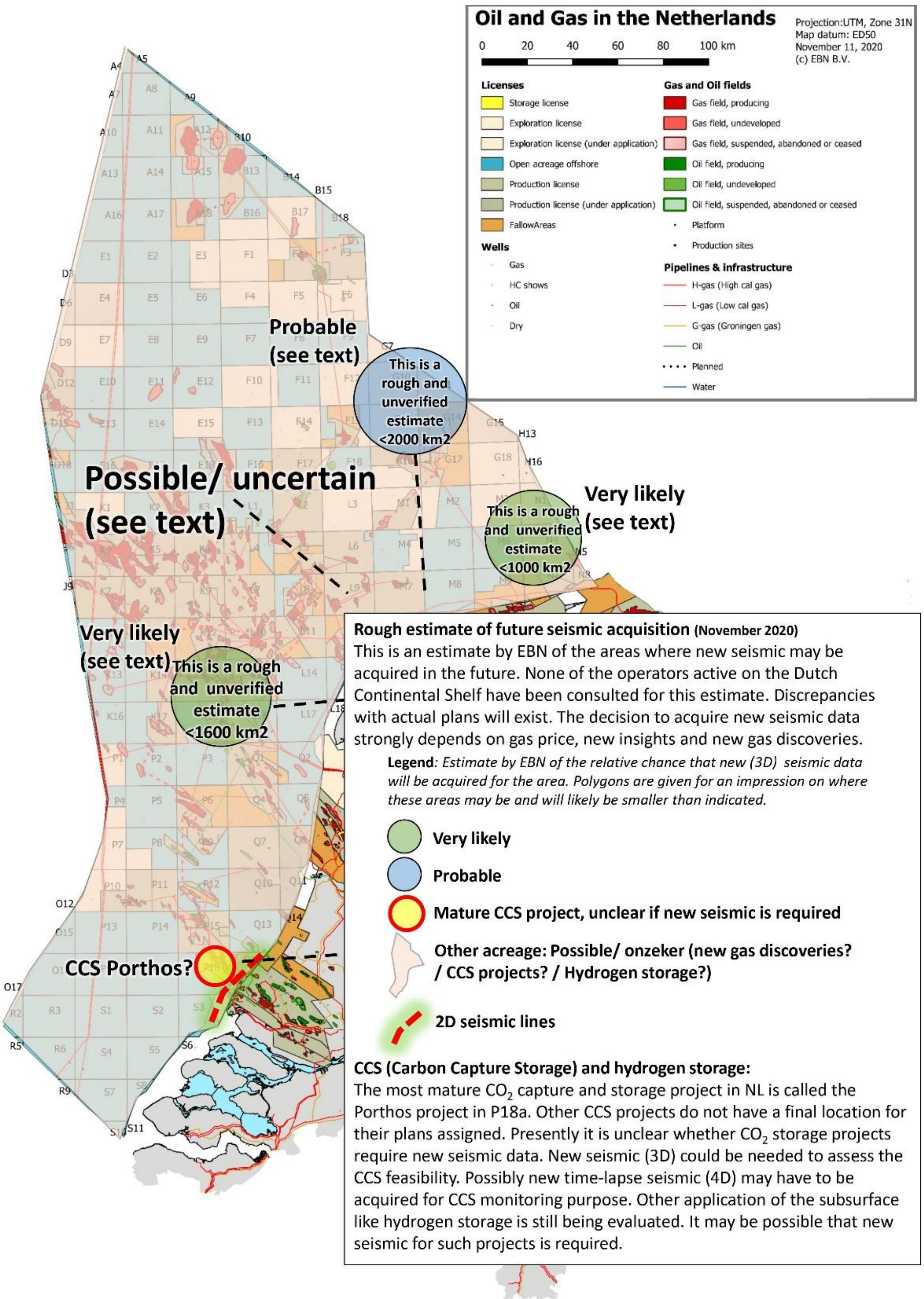

Figure 3-3 Future seismic exploration activities on the DCS (a rough estimation by EBN).

3.4 Ecological impact in relation to developments in seismic surveys

3.4.1 Overlap in time and space

EBN provided an coarse estimation of the scale of future seismic operations and where this might take place on the DCS (see Figure 3-3). In the figure, the green circles represent areas where seismic survey most

likely will take place, and the blue circle is a likely prospect area. Two out of the three prospect areas are located on the eastern side of the DCS, close to the German border.
The estimation of the scale of future seismic operations is based on the current economic situation and expectations, which might change when new gas-fields are discovered, gas prices rise, and offshore seismic exploration becomes more favourable for the oil and gas industry. In order to assess the severity of the effect of seismic exploration activities on the 'indicator' species, future seismic exploration activities were compared to the distribution of the harbour porpoise, harbour seal and Atlantic cod.

Atlantic cod is distributed quite evenly in the Dutch North Sea (Annex A1; Arcadis, 2020). The highest concentration of Atlantic cod in the Dutch waters is during spring, in the most southern corner of the Dutch North Sea. All of the 'likely' and 'most likely' seismic exploration activities take place in the centre of the Dutch North Sea or on the eastern side near the German border. Even when the Atlantic cod is at their highest population concentration in the Dutch North Sea, the population density is very low compared other areas of the North Sea. Therefore, it is unlikely that significant negative effects will occur on population level. As indicator species the cod represents other fish species on the DCS. To be of use for this study there is the need for detailed information on the hearing thresholds, dosis-effect relationships and preferably population models. As these are not available for cod or other relevant species, the potential impacts of seismic surveys on fish will not be further assessed in this CBA.

Although seals can be found traveling and foraging in open water, the harbour seal is mainly bound to coastal waters. The most critical habitats of seals are located in the coastal areas, for example exposed sandbanks for resting and pupping. The occurrence of seals in open water is evenly distributed throughout different seasons, and ranges between 0-0,01 seals/km^2. This means that the offshore seismic exploration is unlikely to have a significant negative impact on the harbour seal population. Additionally, to be of use for this study there is the need for dosis-effect relationships and preferably population models, which are currently not available for these species. Therefore, the potential impacts of seismic surveys on harbour seal will not be further assessed in the CBA. Seismic surveys close to the shore need to be assessed separately because of the conservation goals of the coastal Natura 2000 areas.

The harbour porpoise is widely distributed in the Dutch North Sea waters, with an average occurrence of 0,14 – 3,08 individuals/km^2. This species has been found to be the most sensitive to sound and, based on current knowledge, it is the species that experiences the largest negative effects from seismic surveys on the DCS. Additionally, the harbour porpoise has a low reproduction rate, which might cause limitations in population recovery. The effect of future seismic exploration activities on the harbour porpoise will be calculated and assessed further in this CBA. This will be done, based on harbour porpoise disturbance days.

3.4.2 Ecological impact reference scenario

The reference scenario is based on the past and current seismic activities on the DCS. As elaborated on in paragraphs 2.2 and 3.4.1, the harbour porpoise is used to determine the ecological impact of seismic surveys. To give insight in the ecological impact of the expected 4,600 km^2 seismic exploration (paragraph 3.3), an example of a calculation method is provided in a way that would also be used in an ecological impact assessment. In this example only the harbour porpoise disturbance days will be calculated. There are population models for the harbour porpoise, such as the Interim iPCOD model (used for the KEC as explained in section 2.3.2),however this model is solemnly applicable to piling activities (Booth et al., 2019).

To calculate the number of harbour porpoise disturbance days, the following formula is applied in line with the KEC method:

$$animal\ disturbance\ days = daily\ disturbed\ area * animal\ density * disturbance\ days$$

The required technical specifications are derived from an actual seismic survey, which is planned to take place in the coming years on the DCS. The standard SDS (Streamer Dual Source) method for oil and gas exploration will be applied. From this survey data, a rectangular part of approximately 1,000 km^2 is derived to anonymize the data. The survey characteristics are displayed in Table 3-1.

Table 3-1 Survey characteristics based on a planned SDS seismic survey

Survey area	1,000 km^2
Distance between survey lines	300 m
Number of survey lines	83
Distance between lines to sail in one turn (diameter turn circle)	6.6 km
Average vessel speed	2.3 m/s (4.47 knots)
Number of lines per day	3.6
Number of days (total survey)	75
Number of days with active airguns	40

Daily disturbed area

In this example two different disturbance assumptions will be considered (for more information see Text box 3.1):

1. The harbour porpoise will not return to the disturbed area for 24 hours;
2. The harbour porpoise will be disturbed within a certain radius of the sound source.

For both options an average disturbance distance of 10 km around the seismic source vessel is used (Sarnocińska et al., 2020). The disturbance is based on an airgun array of 3570 in^3.

For the calculation example, based on the above-mentioned survey characteristics, this means the following for the disturbance assumptions:

Disturbance assumption 1: 24 hour disturbance (Animals do not return to the same area within 24 hours)

In order to calculate the disturbed area based on a 24 hour disturbance, the average daily sailing pattern needs to be known. The average daily sailing pattern is derived from the average vessel speed, direction, the length of the sailing lines and the length of the turn circle. This will give insight into the amount of sailing lines per day. Combining these lines with the turn circle diameter and the disturbance distance (10 km) will give the total disturbed area based on the 24 hour assumption. This results in a daily disturbed area of 1616 km^2 (Figure 3-4).

Disturbance assumption 2: radius disturbance (Animals only avoid a radius around the sound source)

When assuming the harbour porpoise is only disturbed in a 10 km radius from the seismic sound source, the surface area of the circle can be calculated by the standard formula $\pi * r^2$ (pi times the radius squared). In this case this results in a daily disturbed area of 314 km^2 (Figure 3-4).

Text box 3.1

A study on the startling response and turnback time to normal behaviour suggests that it can take up to 24 hours for a harbour porpoise to completely return to normal behaviour (van Beest et al., 2018). The same study also suggests that the startling response is specific per individual. Some animals do not respond at all, while others have a drastic flight response. These individual reaction differences in marine mammals are also observed in other studies. This suggests that at least a part of the harbour porpoise population, present in the proximity of the sound source, will be disturbed for up to 24 hours after the seismic survey vessel has passed. However, a recent study by the Aarhus University (Roskilde, Denmark) shows that field observations based on click behaviour of porpoises before, during and after a large scale seismic survey in the North Sea (located just above the DSC) that porpoises only show different behaviour in an eight to twelve kilometre radius around the moving seismic sound source (Sarnocińska et al., 2020). The difference might be explained by means of habituation, a single or start of a sequence of loud noise is likely to get a more startling response than a continuous sequence of noise slowly coming at you and passing by. This gives us two options to calculate the disturbed area.

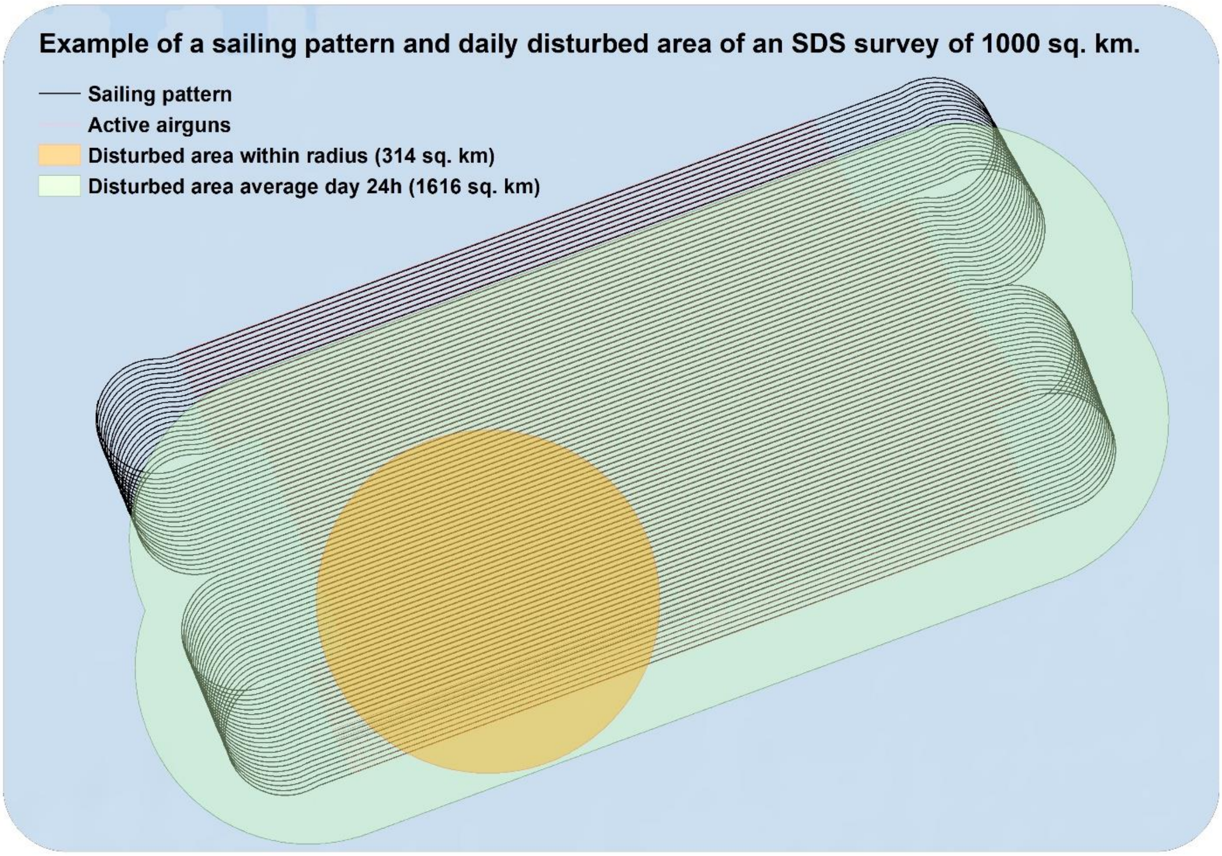

Figure 3-4 Sailing pattern, active airgun area and daily disturbance of an example seismic survey (SDS-method) of approximately 1000 km^2.

Animal density

Usually the average animal density is calculated for the project area, based on the most recent available literature. As the exact locations for the 4600 km^2 are not defined, for this example the average harbour porpoise density is calculated from Geelhoed & Scheidat (2018). In this study harbour porpoise densities are available from 2010 – 2017. The average harbour porpoise density is 0,94 individuals/km^2.

Disturbance days

The disturbance days are based on the number of days in a seismic survey when the airguns are actively shooting. For a seismic survey (SDS method) of 1,000 km^2 approximately 75 days are needed. These days consist of multiple components. The number of days that the airguns are shooting is the combined number of days for shooting, turns and infill & re-shoot. These numbers are based on a continuous 24 hour schedule. In reality the survey will not start, pause or end at precisely midnight. Therefore, two days were added to compensate for start-ups after contractor down-time during the survey. This results in a total of 40 days of animal disturbance for the total survey (Table 3-2).

Table 3-2 Example of a seismic survey activity schedule of a SDS-survey of approximately 1000 km^2.

Activity	Days complete SDS-survey	Days with active airguns
Shooting	17	17
turns	11	17
infill & re-shoot	10	10
contractor down-time	7	(2)
Standby	21	-
Mob./demob.	7	-
Total	75	40

Animal disturbance days

To calculate harbour porpoise disturbance days the above-mentioned formula is applied. For each disturbance assumption a calculation example will be given. The data in the following tables are derived from the calculation example of 1,000 km^2.

Disturbance assumption 1: 24 hours – no return

Variant (SDS-method)	Avg. disturbed surface area km^2/day	Avg. hp density km^2	Days of active exploration (shooting)	Hp disturbance days
24h disturbance, 1,000 km^2	1616	0.94	40	60762
24h disturbance, 2,000km^2	1616	0.94	80	121523
24h disturbance, 4,600km^2	1616	0.94	184	279503

Disturbance assumption 2: radius disturbance

Variant (SDS-method)	Avg. disturbed surface area km^2/day	Avg. hp density km^2	Days of active exploration (shooting)	Hp disturbance days
10km disturbance, 1,000 km^2	314	0.94	40	11806

10 km disturbance, 2,000 km^2	314	0.94	80	23613
10 km disturbance, 4,600 km^2	314	0.94	184	54309

Conclusion

The two assumptions show that a different interpretation of how the harbour porpoise is disturbed can lead to a major difference, approximately a factor 6, in harbour porpoise disturbance days. Additionally, the average density of the harbour porpoise fluctuates on spatial and temporal scale, influencing the outcome of the harbour porpoise disturbance days. For example, the harbour porpoise density in Geelhoed & Scheidat (2018) ranges from 0.14 – 3.08.

The disturbance area of 10 km was based on an airgun array of 3570 and 3360 cu inch. On the DCS the airgun array is not expected to exceed 3400 cu inch. This means that the disturbance area might be a bit smaller. However, the way that the harbour porpoise responds to the disturbance influences the outcome of the harbour porpoise disturbance days more than a slightly bigger or smaller airgun array.

The calculations are based on the standard seismic survey method, SDS. When OBN is used, the survey lines lie closer together and the turn circle is much smaller as there are no lines with streamers behind the research vessel, which reduces the average disturbed surface area per day. However, this is only the case for the 24 hour disturbance. As more lines need to be sailed for the same surface area, the total survey time will increase compared to the standard SDS method. The actual impact differences of OBN and SDS depend mainly on the interpretation of the disturbance behaviour of the harbour porpoise, as the difference in sailing pattern will have more influence on the disturbed area, and the duration of the survey when a radius disturbance is assumed.

The average number of days is based on a seismic survey performed in summer. In seasons where the weather is bad, more shooting hours/days are needed. Additionally, the shape of the example survey is very efficient in relation to shooting and turning time. In the field, this is usually not the case. For example, a rectangular sailing pattern of 1,000 km^2 takes less time to survey than a sailing pattern with an irregular shape with the same surface area.

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4 Seismic regulation Alternatives

4.1 Alternatives overview

The interviews among experts resulted in four main alternatives to regulate the seismic activity on the DCS. The four main alternatives are:

1. Regulating by means of a fixed noise limit
2. Regulating by means of a technical requirement
3. Regulating by means of a noise budget in square kilometres
4. Regulating by means of a noise budget in animal disturbance days (i.e. harbour porpoise disturbance days)

Fixed noise limit

The regulation by means of a fixed noise limit is similar to the current legislation in Germany, as well as the noise budget described in the “kavelbesluiten” for the construction of offshore windfarms in The Netherlands.

Although a fixed noise limit has certain benefits, such as being straightforward for all involved parties, no need of complicated calculations, and being in line with the regulation in one of our neighbouring countries, the experiences from Germany learn that it makes it practically impossible to perform seismic surveys at all. This is not explicitly due to the fixed noise limit regulation, but due to the decibel level of the fixed noise limit. For a noise limit to be ecologically beneficial the decibel level has to be lower than the sound levels needed for seismic exploration. For example, the noise limit in Germany is set to 160dB on 750m from the sound source to ensure there are no significant effects on the harbour porpoise populations. The consequence of this implemented fixed noise limit is that no seismic operator has been able to perform seismic surveys in the German waters (for more information on the fixed noise limit regulations see section 2.3.1).

A similar decibel level, which will exclude seismic exploration from the DCS, can be seen as a good thing ecologically speaking but this is inconsistent with the current line of the Netherlands need for a steady production of Dutch natural gas (as stated in the “Small Field Policy”, see paragraph 2.3.2). This all is of course dependent on the cut-off line of the noise limit, but it is of yet unclear where to draw this line to a limit where effective seismic explorations are still possible.

For the DCS as a whole this method is therefore not suitable as it would severely limit the possibilities of exploration with the current available methods. However, it is not unthinkable to implement a noise limit in certain areas of the North Sea (either with or without seasonal restrictions). For example, a noise limit in the pupping season in the coastal Natura 2000 areas which already holds a conservation goal for seals.

Regulating by means of a technical requirement

Regulating by only allowing certain proven techniques is a common method in different industries. In this case, the best available technique from an ecological or environmental point of view will be obligated to use. This can either be one specific technique or the best available technique at that moment. As the choice of techniques for offshore seismic exploration is very limited, and the environmental and ecological benefits of the new(er) techniques currently in development are yet unclear, this is not a logical step to take. In addition, the Dutch oil and gas industry has already committed itself in the “Noordzeeakkoord” to using the best available technique matching with the seismic information needed..

The two alternatives described above are considered not to be feasible. As the fixed noise limit violates the Dutch policy to be able to explore and extract oil and gas from the DCS. Additionally, the industry already committed to using the BAT. Therefore, these alternatives will not be analysed further in this study.

4.2 Noise budget

The next paragraphs will describe the pros and cons as well as the possible choices within possible regulation strategies of the remaining alternatives; regulating by means of a noise budget in square kilometres, and/or disturbance days.

4.2.1 Noise budget based on a restriction on the surface area

A limit on the amount of seismic activity by a maximum number of square kilometres per year is rather straightforward; It is a clear rule to follow for legislators as well as operators. There are no complicated (noise) calculations needed, only the surface area of the area where the seismic survey will take place. If that fits within the surface area budget (and conservation goals are met) than a permit can be issued.

Some elements need to be considered in the case of a square kilometre budget:

1. What should the size of the budget be based on?
2. Should the budget be fixed or flexible?

To establish a noise budget based on square kilometres the first difficulty is where to base the number of square kilometres on. The number should be low enough to have ecological benefits but large enough to be able to perform commercially viable seismic exploration. Based on the information in chapters 2 and 3 a viable way is to establish the budget on explorations done in the past. In general, seismic surveys have been carried out for more than half a century in the Dutch sector of the North Sea. The fluctuations in the size of the population of harbour porpoises of the last decades show no correlation with these seismic activities. The intensity of seismic survey activities does not therefore appear to negatively impact the conservation objectives for harbour porpoises. Establishing a limit on harbour porpoise disturbance days, based on historic and existing levels of activities, supports avoiding potential impact on the population in the future. Besides, the exploration methods have improved. There is a degree of certainty that current and future explorations will have less noise impact than an equal amount in the past. For example, in the past larger airgun arrays were used, 4700 cu inch compared to the current 3200 cu inch. When considering the average of past explorations, it could limit the larger scaled and possibly cost-efficient surveys in the future. In the last 10 years there were six years with seismic surveys, of which four of them were larger than the average size of the past two decades.

In the 'redeneerlijn seismiek' a proposition is made to base a noise budget on an average surface area of 2000 km^2 per year. This average is derived from seismic explorations between 2005–2014, in which the outliers of 2011 and 2012 were taken half into account. However, when the same calculation is made for the period 2010–2020 the average would be 1450 km^2, due to a lack of seismic surveys in the past five years.

If the noise budget would be based on the 2,000 km^2, this would mean that all three by EBN predicted seismic surveys could take place. However, only one per year based on a fixed budget. If this budget would be flexible, so the unused budget from one year can be added to the budget of the next year, there are practically no restrictions and no ecological considerations. Meaning that the seismic surveys can continue as business as usual. Additionally, the incentive to apply BAT is non-existent with a budget solemnly based on surface area. However, in the North Sea Agreement the oil & gas industry have already agreed to apply BAT. Even if a noise budget would be implemented the seismic surveys would still have to comply with the conservation goals set for Natura 2000 areas and avoid direct physical harm by applying mitigation measures, see paragraph 2.3.3.

4.2.2 Noise budget based on the number of disturbance days

An ecologically better method would be to define a budget based on (harbour porpoise) disturbance days (like the KEC method) derived from the average past impact. This way a seismic survey can be optimised to "cost" as few disturbance days as possible, and possibly be able to cover a larger area with the same amount of ecological impact. On top of that, a set number for harbour porpoise disturbance days is a straight-forward rule for legislators to base the issuing of permits on. On the other hand, detailed information (see paragraph 3.4.2) and calculations are required to determine the impacted area of a specific seismic survey. When using the noise budget based on disturbance days of seismic explorations of the past, it could limit the larger scaled and possibly cost-efficient surveys (combined surveys) in the future. Finally, if a noise budget would be based on frequency weighting, specifically for the harbour porpoise, it might not be beneficial for all marine animals, because different marine animals can have a different hearing and sensitivity range.

For a budget based on disturbance days the following elements need to be considered and included:

- Determine which survey area design and airgun specifics to set as a baseline
- Sound source and sound propagation models
- Different insights in the disturbed area of the species (e.g. behavioural response).
- Animal density

In the calculation example in paragraph 3.3.3 a disturbed area was assumed. For a noise budget based on disturbance days it is essential to calculate the disturbed area. The same calculation methods and models need to be used for calculating the noise budget as well as the budget needed for every future seismic survey alternative. This way different alternatives to perform seismic surveys can be compared to find out how much of the budget is needed per alternative.

To determine the survey area design and airgun specifics, the disturbance days budget could be based on the seismic survey methods and airgun size in the past. Based on the information acquired from the interviews, this would mean a standard SDS method and an airgun size of about 3400 in^3. Considering the behavioural response of the harbour porpoise as described in Textbox 3.1, either the total disturbed surface area during one day or the continuous disturbance at any moment in time caused by the sound source should be multiplied by the total amounts of days with airgun activity, and the average number of animals per square kilometre (see calculation and example in paragraph 3.4.2).

In theory a noise budget based on disturbance days is promising, the implementation however, is rather difficult. The assumptions regarding the animal disturbance alone will give an estimated difference of a factor six in the disturbance days budget. Additionally, at the moment there is not a combined sound source and sound propagation model available that is agreed on by all the involved stakeholders. On top of that, the current available models have their limitations, especially for an innovative method like the e-source guns in combination with frequency weighting (section 3.2). Furthermore, the historical data of the harbour porpoise distribution on the DCS is fluctuating per location per year. This could mean that when using the latest animal count, or updated animal distribution model for calculating the budget of a new seismic survey on a specific location that only a small area can be seismically explored. For example (simplified); if the budget is based on a surface area of 2000 km^2 with an average animal density of 1 animal per km^2, and the latest insights show an animal density of 4 per km^2, only an estimated area of 500 km^2 can be surveyed. On the other hand if the latest insight show an animal density of 0,25 animals per km^2 a survey up to 8000 km^2 is possible within the same budget.

The only way to address these issues is to agree on all assumptions in advance and keep those assumptions in future calculations. It will however be hard to implement new scientific insights without completely re-calculating the available budgets which could lead to uncertainties in the possibilities for the industry.

One of the reasons to implement a noise budget based on disturbance days is to have an incentive to use more eco-friendly methods. However, in the North Sea Agreement the oil & gas industry have already agreed to apply BAT, and with a limited number of available seismic survey methods it is questionable whether a noise budget would improve the currently available methods for seismic survey.

Even if a noise budget would be implemented the seismic surveys would still have to comply with the conservation goals set for Natura 2000 areas and avoid direct physical harm by applying mitigation measures, see paragraph 2.3.3. Theoretically, a noise budget could lead to more seismic exploration than the current situation. With the current situation a permit application can be declined by the authorities because of cumulation with other projects. For example, the ecological negative effects of the combined underwater noise of the construction of offshore wind parks and seismic exploration can be assessed as to high and significantly detrimental for the marine environment. However, when there is a set noise budget for seismic survey activities a permit application within the budget cannot be declined based on activities from other sectors.

5 Economic impact

5.1 Introduction

The scope of a CBA, as explained in 1.2.2, is to analyse how a project or intervention impacts society as a whole. The ultimate goal is to measure, quantify and valuate these changes ('effects') as far as possible in monetary terms, enabling a comparison of different options in uniform terms. This analysis requires that for each of the alternatives, it is clear what 'physical' effects occur compared to the reference scenario. The quantification and valuation of the effects also requires data.

For the current analysis, some of the 'links in the chain' are missing: several alternatives exist, as has been explained in chapter 4, but it is not yet possible to distinguish what the differences between these alternatives means in terms of the number and size of seismic surveys that can or cannot take place, the costs at which they can take place, the amount of gas that can or cannot be produced from the Dutch Continental Shelf, and the impact on the marine life in the North Sea. Without this information it is not possible to accurately quantify and valuate the effects that occur in each of the alternatives in a plausible manner.

Considering these unknowns and the inherent uncertainty in quantifying the relevant effects of underwater noise, the analysis will therefore start by exploring two extreme scenarios:

(1) No additional restrictions will be introduced for seismic surveys on the DCS (i.e. the reference scenario of this CBA)
(2) A noise budget will be introduced and as a result, seismic surveys will no longer be possible.

Both scenarios are perhaps not very realistic as such, but they serve to create a 'continuum' in which the project alternatives (discussed in chapter 4) can be placed to compare them to each other and to the reference scenario.

We will discuss the following effects in relation to these two extreme scenarios:

- ecological impacts on marine life;
- economic impacts of gas production / imports;
- security of supply of natural gas;
- emissions of natural gas production and transmission.

5.1.1 Scenario 1: No additional restrictions

Chapter 3 explained the reference scenario for this study. When no additional restrictions such as a noise budget are imposed on the oil and gas industry, current regulation and commitments continue to rule seismic surveys. This includes the industry's commitments under the Noordzee Akkoord to:

- do research on how the ecological impact of seismic surveys can be reduced;
- deploy the Best Available Technology (BAT) which causes the least harm to marine life, whilst not impairing the ability to get the data the companies need;
- enter into discussions whenever there are indications that despite deploying BAT, ecological damage cannot be avoided.

Particularly this last point is of great importance for our current purpose. While the commitments focus on the minimisation of disturbance, it is not the ‘total and absolute’ avoidance of ecological damage that is leading in the other commitments, but the industry’s ability to gather the data. While “entering into discussions” is no guarantee and does introduce some uncertainty in terms of how much ecological impact could still remain, it is expected that anything other than an impact on the population below 5% would be an unacceptable outcome of such discussions for the government.

Several other factors are relevant, including the following:

- Thus far, no research has been conducted on the relation of the effects of seismic surveys and the impact on the population of harbour porpoises on the DCS. Additionally, it should be noted that simultaneous disturbance from construction of offshore wind farms and seismic surveys was hardly or no factor of importance. Also, impact on other species is less clear.
- Technology is gradually improving, thereby potentially reducing the impact of seismic surveys in the long run.
- Few surveys are currently planned, although this is a function of economic cycle, fiscal policy, global prioritization of opportunities by oil and gas companies, other regulatory issues (most notably nitrogen deposition), etc.

The idea of a noise budget is perhaps driven more by a need to gain more control over and clear, transparent evaluation of permits than achieving an actual reduction of seismic surveys. Without a noise budget, the number or total area of seismic surveys would not necessarily be (much) more than it would be with a noise budget. The same goes for the impact of seismic surveys in the North Sea ecological system. The two risks of not having additional restrictions on underwater noise from seismic research, from an ecological point of view, are:

(1) Surveys being combined for reasons of economies of scale. This is a risk because it is yet unknown what the ecological impact is of such a peak of impulse sound, particularly when combined with underwater noise from other sectors.

(2) Surveys taking place simultaneously with significant disturbance caused by other sectors, in particular the construction of offshore wind farms. Given the preference for any offshore work in the same season due to weather conditions, this is a very relevant issue.

The potential ecological impact of these risks has been discussed in section 3.4. Note that an implementation of a noise budget with any kind of flexibility could also open the door to these ecological risks, as economies of scale and a preference for a season when working offshore, are exactly the reasons why the industry argues that a noise budget would only be acceptable when some form of flexibility exists; this will be discussed further in section 5.3.2. As this part of the analysis focuses on extremes, these two risks will be explored first, before moving into a more nuanced discussion of the impact of different varieties of a noise budget (the alternatives).

As explained in section 3.3, the surface area where seismic surveys are likely (acknowledging the uncertainties which affect the actual needs for seismic surveys in the future), leads to an estimated and indicative number ranging from 54,309 to 279,503 harbour porpoise disturbance days.

The economic impacts of gas production/ imports, security of supply, and environmental effects are not further discussed here. Any changes occurring in the future in terms of these effects, are by definition not an impact of the additional restrictions imposed by the introduction of a noise budget.

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5.1.2 Scenario 2: No more seismic surveys

On the other extreme side of the spectrum, there is the scenario where additional regulation in the form of a noise budget would be the end of seismic surveys on the Dutch Continental Shelf.

A noise budget by itself shouldn't necessarily mean that seismic surveys are out of the question. It has even been suggested in the interviews for this study that a noise budget might actually enable permitting as there is more clarity on the framework to decide on requests for seismic surveys. This would depend to a large extent on the choices made in the definition and implementation of the noise budget.

This extreme scenario may be considered more realistic when bearing in mind that the oil and gas industry and more specifically, the seismic survey industry, is already in rough weather. The Dutch offshore oil and gas industry competes internationally for funding and the combination of shrinking potential volumes with high costs and low prices means that its priority is declining (WoodMacKenzie, 2019). Any change that raises the capital and/or operational costs, or risks, of the exploration phase is detrimental to their business and could push it beyond a tipping point. The offshore infrastructure for transmission of natural gas to the mainland is also ageing while the potential volumes will increasingly need to be transported along larger distances as production platforms are being decommissioned (EBN, 2018). Postponing seismic surveys can lead to a situation where the infrastructure that is required to transport that gas to the mainland is no longer available and the new volumes alone cannot justify investments in new infrastructure. On the other hand, newcomers to the market do have different investment policies and requirements, and joint efforts by the industry (including increasing cooperation between offshore operators) help to reduce costs.

Naturally, the noise budget only pertains to seismic surveys as part of the exploration, not the other steps in exploration or the production as a whole. Current production is not affected by a potential implementation of a noise budget, only the discovery of new reservoirs in areas which are to date not surveyed with 3D surveys of sufficient quality. The 2019 annual report "Delfstoffen en aardwarmte" published on the NLOG website shows that in the next 25 years, 42 billion cubic metres (bcm) of natural gas is expected to be produced from reservoirs that are yet unproven, roughly equal to the total current domestic gas consumption in The Netherlands during one year. On an annual basis, the volume varies between 1 – 3 bcm, representing up to 10% of the annual gas consumption of The Netherlands in any year.

Assuming that for any fraction of this volume to be produced, seismic research is required and further assuming that a noise budget makes further seismic research impossible, the most extreme scenario would be that this 42 bcm would not be produced if a noise budget were to be implemented. Considering the demand for natural gas as autonomous, this volume would need to be replaced by other sources.

A study done by CE Delft (Vergeer *et al*, 2015) provided insight into the effects of replacing gas produced from the Groningen field by either gas imported from Russia through pipeline, imported from Qatar as LNG, produced offshore or avoided by energy saving measures. For our current purpose, we focus on replacing offshore produced gas with imported gas from Russia. Given the current and future restrictions on the Groningen field, import of Russian gas is the most plausible alternative for gas not produced from small gas fields in The Netherlands. We use the comparison made in the CE study of both options to Groningen to make a comparison of gas from small fields vis-à-vis Russian gas imports. The CE study uses a volume of 10 bcm as a reference[10], for our purpose we are interested in the effects associated with a volume of max. 42 bcm.

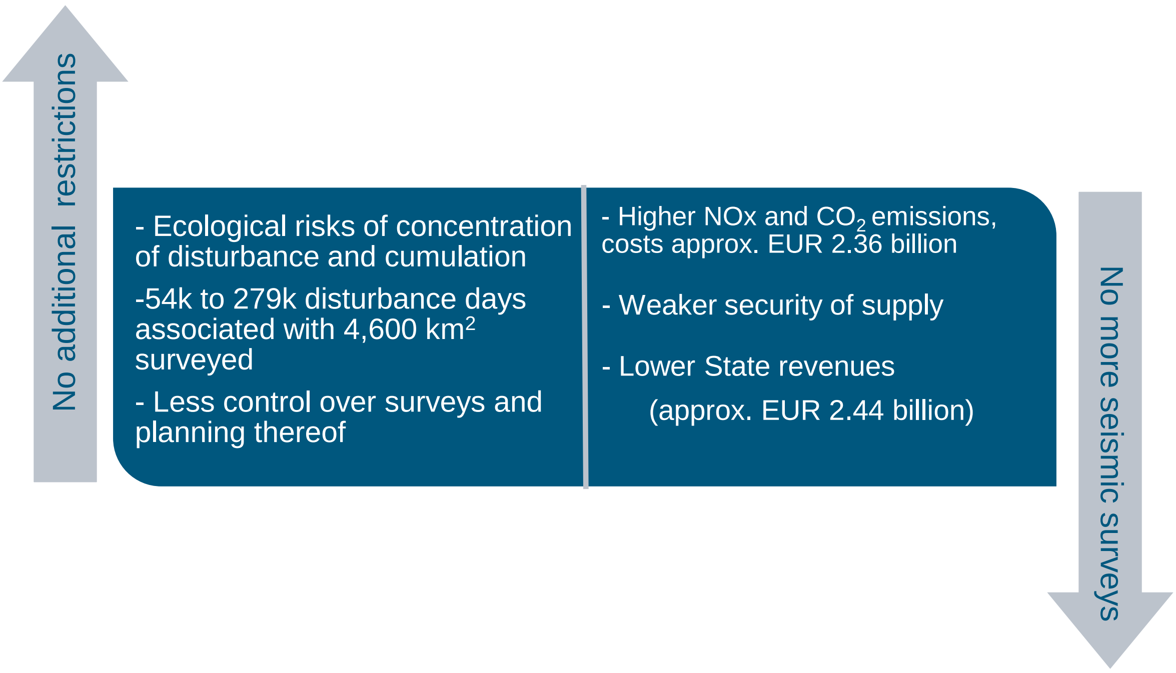
[10] Technically, the report speaks of 10 bcm per annum, but the avoided emissions refer to those that are associated with 10 bcm of produced and transmitted natural gas, regardless of the time period.

Based on the findings in the CE report we can conclude[11]:

- Emissions associated with importing the 42 bcm of natural gas from Russia instead of production on the DCS would be significantly higher:
  - NO_x emissions[12]: 15 kton higher;
  - GHG emissions: 20 Mton CO_2 eq. higher;
  - the monetary value of these emissions would be roughly EUR 2.36 billion in present value[13].
- The impact of importing more gas from Russia is deemed to have a minor negative impact on the security of supply of natural gas for The Netherlands, while gas from offshore fields has a positive impact in the long run.
- The revenues for the Dutch State are expected to decline by EUR 3.5 billion when gas from small fields is replaced with imported gas from Russia. This represents a loss of EUR 2.44 billion in present value terms.
- The impact of gas imported as LNG (e.g. from Qatar) is even higher than gas imported from Russia, especially in terms of the environmental effects.

While there are some caveats in using these figures for our current purpose[14], these numbers do provide an indication of the magnitude of the effects that occur when the 42 bcm of natural gas would not be produced from offshore fields.

The figure below summarizes the findings from our two extreme scenarios.



[11] The emissions associated with imported gas to replace gas from offshore fields as just described should be net of emissions which would be associated with carrying out seismic surveys. However, our initial estimate concluded these emissions to be relatively insignificant.
[12] Most of which emitted in Russia
[13] This is a rough approximation, using a NOx price of EUR 34,7 /kg (CE Delft Handboek Milieuprijzen, 2015), a current CO2 price of EUR 95/ton (two degrees scenario) and a 3% social discount rate, assuming an even spread over 25 years.
[14] Such as: the data used in 2015 may not be fully up to date, Groningen was used as a reference, linear extrapolation of 10 bcm to 42 bcm while perhaps not all relations are linear.

The analysis thus far can be considered to be a simplification of the problem, however it is useful in discussing the different variations of an intervention in the form of a noise budget. To bring more nuance in this discussion, the relevant questions are:

- how much seismic surveying is required to make production of the 42 bcm possible;
- how would those surveys be affected by different variations of a noise budget;
- what would be the ecological impact of those surveys.

As for the first question, it stands to reason that the best possible answer with the currently available information is the estimated area of 4600 km^2, although this estimate is subject to a lot of uncertainty and can be higher as well as lower. It is also possible that more surveys could increase the amount of gas still to be produced if gas fields are found that are larger than expected. The third question has been discussed to the extent possible in 3.4 when the disturbance caused by the currently expected surveys was estimated.
The second question is discussed in the following sections of this chapter, although the answer largely depends on the exact form and parameters of a noise budget.

5.2 Potential impact of a noise budget

Now that we have discussed the two extreme scenarios, we can zoom in on the different alternatives for a more nuanced discussion within the framework constructed so far. More regulation in the form of a noise budget can affect seismic surveying in different ways:

- It can make seismic surveys more expensive, either by
  - requiring more expensive technology to minimise impact and still be able to survey the desired area;
  - causing surveys to be reduced in size, in order to stay within the annual budget, making the surveys less efficient;
  - surveys taking place in a less favourable seasons, when a seasonal restriction is part of the noise budget, leading to a longer duration to cover the same area;
  - risk of failed surveys in case non-proven techniques must be used.
- It can cause seismic surveys to be postponed as the budget for a certain year has already been exhausted by other surveys.
- It can make them more difficult to plan as it requires coordination between different operators (assuming the budget applies on an industry level).

5.2.1 Higher costs

When increased regulation leads to higher costs, the question is whether the costs increase to the point where the exploration and production of that field become unfeasible. If not, the only impact is the increase in resources needed in the seismic survey industry. If it does (make exploration unfeasible), the government could evaluate options to compensate the sector for higher costs of seismic surveys, e.g. through fiscal measures. It should be kept in mind that seismic survey costs occur upfront, so higher costs raise the risk profile while the compensation may only apply once a field is taken into production. It could also be argued that the industry has also committed to the application of BAT (in terms of minimal disturbance), which implies that the costs of applying BAT don't jeopardise the feasibility of exploration and production of offshore gas fields on the DCS. The same argument doesn't hold when it is the economies of scale which are under threat of regulation, though. When seismic surveys have to be split up in several separate surveys as a result of regulation, the costs can increase to levels which the O&G didn't anticipate when committing to applying BAT. Finally, one of the reasons the government is evaluating a noise budget is because it gives the sector an incentive to innovate and achieve more (data acquisition) with less (disturbance).

5.2.2 Postponement

Assuming that the supply of gas from small offshore fields is finite (i.e. limited to the aforementioned 42 bcm), any effects from postponing the production due to later seismic surveying as a result of increased regulation would be offset by higher than BAU production in later years (disregarding the time value of monetary impacts). The effects become much more pronounced when delay means cancellation. This could be caused by a number of reasons, including those aforementioned (ageing offshore infrastructure with new fields increasingly located at larger distance and relatively small volumes, and the financial situation of the industry), but also the increasing use of the North Sea for offshore wind farms[15] and shipping which present difficulties for the execution of seismic surveys (EBN, 2018).

5.2.3 Planning

The implication of a noise budget would be that there is a limitation on an industry level as to how much surveying can be done. The industry consists of many players and the question is how a noise budget would be translated to these individual companies, or in other words: how is the budget to be allocated between interested parties? Different options exist, such as First Come First Serve (FCFS), auctioning of 'sound rights', a cap and trade mechanism, negotiation with-in the industry organisation (NOGEPA), etc. Each mechanism has its (dis)advantages, but for all of these options it can be argued that planning seismic surveys becomes more complex and will probably require more coordination.

5.3 Comparing different alternatives and choices

We have now discussed the two extreme scenarios, 'No further restrictions on seismic surveys' and its impact on ecology, and 'No more seismic research' with its impact on the sector and the economy. The previous section looked into the ways how a noise budget could affect seismic surveys. This section will look into the different choices and variations that can be made in a noise budget, as explained with their pros and cons in chapter 4, and discuss how this influences the effects discussed in 5.1.1

5.3.1 Area versus disturbance

A noise budget in terms of a maximum area is less efficient in the sense that it doesn't reward the deployment of innovative technologies that enable doing the same or more amount of seismic surveys with less disturbance. That means that a noise budget based on a maximum surface area is more likely to lead to diseconomies of scale when surveys cannot be combined or need to be split.

Provided that a robust model exists to accurately estimate the amount of disturbance caused by seismic surveys, a noise budget in terms of a maximum number of disturbance days would be the approach that has a better chance of optimising the balance between economic and ecologic impacts of seismic surveys. On the other hand, when there is uncertainty about the method or outcome of an estimation of disturbance, it can be difficult for operators to plan surveys.

5.3.2 Flexibility

Bringing in some degree of flexibility can alleviate some of the negative effects of a noise budget, while it can also exacerbate some of the concerns that gave rise to the idea of a noise budget in the first place. Flexibility can take different forms, such as schemes to compensate a smaller area surveyed in one year with a larger area in the preceding or next year[16], conditional approval to combine multiple surveys, periodic negotiations to deviate from a predefined limit, etc.

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[15] This is particularly relevant as there are areas where both offshore wind farms are planned and seismic surveys are expected
[16] This could be regarded as a of Make-Up / Carry-Forward scheme as it is known in energy supply contracts or taxation for instance.

5.3.3 Noise level based on 'existing use'

The level of the noise budget, either expressed in square kilometres or a number of disturbance days, is of course a major (if not the crucial) element in defining the impact of a noise budget.

In terms of the area corresponding with average 'existing use' of the seismic survey industry in the past,, 2.000 km^2 has been suggested in the *Redeneerlijn voor het omgaan met seismische surveys in relatie tot de ecologische effecten van onderwatergeluid*, although the number 2.500 km^2 also came up in some of the interviews. From the interviews with EBN and NOGEPA, it has become clear that, while an upper limit of 2,000 – 2,500 km^2 could be acceptable under certain conditions, beyond a certain lower limit, 'diseconomies of scale' start to occur and seismic surveys can, exceptions notwithstanding, no longer be done in a feasible manner.
EBN indicated that the smallest currently expected survey covers an area of roughly 1,000 km^2. Numbers of 600 – 700 km^2 up to 1,200 km^2 have been mentioned in interviews as the lower limit, but a solid estimate of this parameter is not currently available. Both the lower limit and the upper limit are highly relevant, as they determine what the impact will be of a noise budget: if it is determined at or above the upper limit, there will effectively be no limitation on seismic surveys and the impacts as discussed in that extreme scenario would apply. If the noise budget restricts surveys at or below the lower limit, the effects of the other extreme, no seismic surveys, would apply. The impacts become less straightforward:

- in between the lower and upper limit;
- when flexibility is introduced;
- when a noise budget is combined with other restrictions (seasonal, geographic).

In those scenarios, more detailed data and projections are required to allow quantification.

Taking the suggested 2,000 km^2 area p.a. as a starting point, the following observations can be made:

- The number of marine mammal disturbance days would be in the range of 23,613 to 121,523 per annum. Assuming the same amount of expected seismic surveys will be applicable, but spread over multiple years, the total disturbance would be the same as the range for 4,600 km^2, i.e. 54,309 to 279,503 marine mammal disturbance days. It must be noted that the impact on the population between these two scenarios (potentially surveying 4,600 km2 in one year versus spreading it across at least three different years) can be very different, but there is currently too much uncertainty to draw conclusions. But from the perspective of number of disturbance days, there is no ecological benefit as the total volume of seismic surveys and the associated disturbance as measured by number of disturbance days doesn't change compared to the current situation. This is relevant, as the number of disturbance days is one of the proposed units of a noise budget.
- Given the comments made about the economies of scale it is possible that a restriction of 2,000 km^2 per year or 23,613 – 121,523 disturbance days could lead to somewhat higher costs, but it is unlikely that this would be in the order of magnitude of the almost EUR 5 billion incurred in the extreme scenario when no more gas is produced from new fields on the DCS. Given the uncertainties and lack of data, for the sake of simplicity we assume that the additional economic costs would be negligible.
- The additional regulation in the form of a noise budget does not yield ecological benefits in terms of avoided marine mammal disturbance days (but could in terms of the impact on population), nor does it lead to (substantially) higher economic costs. The remaining argument in favour of a noise budget based on 'existing use' would then be more protection against concentration of disturbance (either through combinations of large surveys or through cumulation with the offshore wind sector) and more control for regulatory bodies in the permitting process.

5.4 Conclusion

This chapter focused on the economic impacts which can occur as a result of the introduction of a noise budget. Given the fact that there are a lot of variables, many of which are currently unknown, two extreme scenarios were analysed. In the first extreme scenario, there are no further restrictions imposed on seismic surveys in terms of sound (this is effectively the reference scenario). This poses ecological risks, gives the authorities less control over the (planning and amount of) surveys and could lead to an estimated and indicative range of 54 to 280 thousand harbour porpoise disturbance days. In the second extreme scenario, no more seismic surveys are held on the DCS due to the implementation a noise budget. The implication of that would be that more gas needs to be imported, leading to approximately EUR 4.8 billion in costs to society due to higher emissions of NO_x and GHG (2,4 billion) as well as lost state revenues (also 2.4 billion), while weakening the security of supply.

When zooming in on a noise budget based on the historic average of seismic surveys, an area of 2,000 km^2 is taken as a starting point, or, the disturbance associated with such an area. In that scenario, the conclusion is that there are no ecological benefits in terms of avoided marine mammal disturbance days (but there could be in terms of the impact on population), nor does it lead to (substantially) higher economic costs.
The remaining argument in favour of a noise budget based on 'existing use' would then be more protection against concentration of disturbance (either through combinations of large surveys or through cumulation with the offshore wind sector) and more control for regulatory bodies in the permitting process.

It has to be emphasized that the analysis requires a lot of "heroic" assumptions of unknown variables, including the amount of seismic surveys that would be done without any further regulation, the impact of that amount of surveying on the ecological system, the impact of potential regulation in the form a noise budget on the seismic surveys, the form and parameters of such a budget and the conditions as to how it is implemented. In our opinion, the value of this analysis lies less in the figures and more in the insight into the effects that occur and how those effects are subject to choices that are yet to be made.

6 Conclusion and recommendations

The aim of this study was to answer two questions: whether the implementation of a noise budget would be an effective method to reduce the ecological impacts of seismic surveys and what an effective noise budget could be for seismic surveys. Below summarizes the main conclusions and recommendation of this report.

Reference scenario
Based on interviews it appears that the industry has plans to carry out a limited number of 3D surveys in the next 5-10 years, with a total estimated surface area of 4,600 km^2. It is hard to accurately forecast the size of the area that will be surveyed in the coming years, as this highly depends on the oil and gas prices, the economic climate and Dutch energy policies. At present commonly used mitigation measures are applied during seismic surveys, such as a soft start, which will scare the animals away avoiding direct physical harm due to seismic surveys on mobile species like marine mammals and pelagic fish. The effect on other organisms, that cannot escape the noise, is as of yet largely unknown.

All seismic projects will need to apply for a Dutch Nature Conservation permit. This entails an assessment of the ecological impact and of the conservation goals of the possibly effected Natura 2000 areas and the concerning protected species.

Alternatives for a noise budget
The following noise budget alternatives were presented in this study: regulating by a noise limit, regulating by technological limitation, regulating by square kilometres and regulating by disturbance days. Of the four alternatives the first two alternatives, regulating by a noise limit similar to a noise limit set for piling of offshore

wind foundations and technological limitations, are not deemed to be technically or economically feasible. The reason is that the fixed noise limit violates the Dutch policy to be able to explore and extract oil and gas from the DCS and the industry already committed to using the BAT (see North Sea Agreement).

This leaves the latter two alternatives, regulating by means of a noise budget based on square kilometres or (harbour porpoise) disturbance days. The ecological and economic effects of both alternatives highly depend on the limit set in terms of the number of square kilometres or the number of disturbance days. However, at this stage there is too much uncertainty surrounding the impacts of seismic surveys on marine species to determine an effective noise budget.

Thus, the alternatives are discussed on a more general level. The benefit of both alternatives is that they are quite straight forward for regulators. On the other hand, if implementing a noise budget based on square kilometres (in this case we assumed the historic average of 2000 km^2) this would not give an incentive for companies to apply the BAT and is effectively not much different from the reference scenario. A noise budget based on disturbance days would give more incentive to conduct the surveys as efficiently as possible with the least amount of disturbance days (hence ecological impact). However, for this alternative, the determination of the maximum allowable number of disturbance days requires more complicated calculations.

Costs and benefits of a noise budget

Because there is so much uncertainty surrounding the relation between a noise budget and seismic research and the relation between seismic research and disturbance, a 'proper' CBA on different variations of a noise budget was not possible. Instead, we looked at two extreme scenarios:

In the first extreme scenario, there are no further restrictions imposed on seismic surveys in terms of sound (this is effectively the reference scenario). This poses ecological risks, gives the authorities less control over the (planning and amount of) surveys and could lead to an estimated and indicative range of 54 to 280 thousand harbour porpoise disturbance days. In the second extreme scenario, no more seismic surveys are held on the DCS due to the implementation of a noise budget. The implication of that would be that more gas needs to be imported, leading to approximately EUR 4.8 billion in costs due to higher emissions of NO_x and GHG as well as lost state revenues, while weakening the security of supply.

When introducing a noise budget based on the historic average of seismic surveys there are no ecological benefits in terms of avoided marine mammal disturbance days. The interviews made it clear that reduction of seismic research activity is not the intended purpose of a noise budget. However, there could be an ecological benefit in terms of the impact on population. The introduction of a noise budget alone is not expected to lead to (substantially) higher economic costs. The argument in favour of a noise budget based on 'existing use' would be that it gives more protection against a concentration of disturbance (either through combinations of large surveys or through accumulation with the offshore wind sector) and more control for regulatory bodies in the permitting process.

Recommendations

Recommendations that follow from this study are:

- To deal with the present uncertainties the noise budget (or other means of regulating seismic surveys) should be flexible. Flexibility enables parties to adapt to changing circumstances (such as the economic cycle), benefit from developments such as new technologies and respond to new information, for example effects of disturbance on ecosystems. To provide some sort of stability and certainty, a mechanism could be proposed where a default value is established (e.g. an annual budget based on existing use) that will enter into force unless parties agree otherwise. To incentivise both the authorities and the industry to enter negotiations, the default arrangement should leave an 'upside potential' for both sides of the table; there has to be something to gain from negotiating. For the government, it could be to reduce the area in years where accumulation with other offshore sectors (wind farms) is expected to occur. For the industry, it could be the possibility to combine several surveys and benefit from economies of scale. Uncertainty reduces as time progresses, and flexibility allows both parties to benefit from that reduced uncertainty.

- In order to be able to decide on an effective noise budget level (such as the amount of harbour porpoise disturbance days) the following will first need to be accomplished:
    - A proper sound model needs to be developed specifically for seismic surveys that can estimate the impact of seismic surveys on the environment as accurately as possible.
    - A population model would need to be developed (or customized) to determine the impact of the predicted underwater noise on the population of sensitive species (to start with the harbour porpoise)
    - The input parameters for these models will need to be agreed upon. Potentially the working groups created for the North Sea Agreement could be used to discuss this.
    - Conduct further research into ecological impact of peak disturbance when combining multiple surveys
    - Do note that the above is quite a time-consuming process which can take a few years.

- To incentivise the deployment and especially the improvement of BAT for seismic surveys, it is advisable to implement regulation on, at least, European or OSPAR level.

- Little is known about the effects of underwater noise on other marine species besides marine mammals. Also, knowledge on impacts on the marine ecosystem level are scarce. However, reducing underwater noise or implementing a noise budget could also have a positive effect on marine species other than marine mammals such as birds, fish, turtles and benthic organisms. It is advised to also investigate the impacts of other sensitive species especially non-mobile species and conduct a study on the correlation between anthropogenic activities and species distribution/mortality (Ijsseldijk & Doeschate, 2020).

- Once there is a noise budget, the way the budget is allocated between interested parties needs to be determined. Different options exist, such as First Come First Serve (FCFS), auctioning, grandfathering, cap and trade, negotiation with(in) the industry organisation (NOGEPA), etc. Each mechanism has its pros and cons[17]. This needs to be discussed within an organisation such as NOGEPA.

[17] *Although the sound budget would be different in nature to GHG emission allowances, some insights can be taken from economic literature on the subject of allocation methodologies. One example of such literature would be Alvarez, Francisco & André, Francisco (2013). Auctioning Versus Grandfathering in Cap-and-Trade Systems with Market Power and Incomplete Information. FEEM Working Paper. 98. 10.2139/ssrn.2362888.*

- It is still unclear whether the combined noise from all the current activities, including the construction of offshore windfarms, is going to be within the resilience of the populations of different species. Noise should therefore not be looked at per sector or per activity, but in combination with different activities, both spatially and in time. It is recommended to introduce a noise budget for all activities, instead of defining a budget per individual activity. For example: A total noise budget for DCS expressed as a maximum percentage of surface area exposed to a certain level of noise (similar to the German regulation). This can also be considered in combination with a limit on the number of international projects conducted simultaneously, however this would require significant collaboration and information exchange between different North Sea countries.

- If a multiple sector combined noise budget is not possible or desirable, it is advisable to ensure that no simultaneous large-scale activities with a major impact regarding noise disturbance take place. This can be safeguarded, for instance, in joint consultation between the government and the various sectors (for example in the bodies used for the North Sea Agreement). A possible follow-up step is to investigate the possibilities of developing an (international) spatial planning tool that visualises when and where which activity will take place.

7 List of references

Aarts, G., Cremer, J., Kirkwood, R., van der Wal, J. T., Matthiopoulos, J., & Brasseur, S. (2016). *Spatial distribution and habitat preference of harbour seals (Phoca vitulina) in the Dutch North Sea*.

Bohne, B.A., Thomas, J.A., Yohe, E.R., & Stone, S.H. (1985). *Examination of potential hearing damage in Weddell Seals (Leptonychotes weddelli) in McMurdo Sound, Antarctica*. Antarct J US, 20:174-176

Carroll, A. G., Przeslawski, R., Duncan, A., Gunning, M., & Bruce, B. (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. *Marine Pollution Bulletin*, *114*(1), 9–24.

Ecosystemen (2017) Bruinvis langs de Nederlandse kust, 1970 – 2015. Retrieved from: https://www.clo.nl/indicatoren/nl125006-bruinvis-langs-de-nederlandse-kust.

Engås, A., Løkkeborg, S., Ona, E., & Soldal, A.V. (1996). *Effects of seismic shooting on local abundance and catch rates of cod (Gadus morhua) and haddock (Melanogrammus aeglefinus)*. Can. J. Fish. Aquat. Sci.,53 , pp. 2238-2249

Enger PS (1981) Frequency Discrimination in Teleosts—Central or Peripheral? *Hearing and Sound Communication in Fishes*. Springer, New York, NY, p 243–255

Erbe, C. (2013). International regulation of underwater noise. *Acoustics Australia*, 8.

Finneran, J. J. (2015). Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. *The Journal of the Acoustical Society of America*, *138*(3), 1702–1726.

Geelhoed, S. C. V., & Scheidat, M. (2018a). Abundance of harbour porpoises (Phocoena phocoena) on the Dutch Continental Shelf, aerial surveys 2012-2017. *Lutra*, *61*, 127–136.

Geelhoed, S. C. V., & Scheidat, M. (2018b). *Abundance of harbour porpoises (Phocoena phocoena) on the Dutch Continental Shelf, aerial surveys 2012-2017*.

Gilles, A., Viquerat, S., Becker, E., Forney, K., Geelhoed, S. C. V., Haelters, J., Nabe-Nielsen, J., Scheidat, M., Siebert, U., Sveegaard, S., Van Beest, F., Van Bemmelen, R., & Aarts, G. (2016). *Seasonal habitat-based density models for a marine top predator, the harbor porpoise, in a dynamic environment*.

Halvorsen, M. B., Casper, B. M., Matthews, F., Carlson, T. J., & Popper, A. N. (2012). Effects of exposure to pile-driving sounds on the lake sturgeon, Nile tilapia and hogchoker. *Proceedings. Biological Sciences*, *279*(1748), 4705–4714.

Halvorsen, M. B., Casper, B. M., Woodley, C. M., Carlson, T. J., & Popper, A. N. (2012). *Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds*. *PloS One*, *7*(6).

IJsseldijk, L. L., ten Doeschate, M. T., Brownlow, A., Davison, N. J., Deaville, R., Galatius, A., ... & Heesterbeek, H. (2020). Spatiotemporal mortality and demographic trends in a small cetacean: Strandings to inform conservation management. Biological Conservation, 249, 108733.

Jensen, L. F., Teilmann, J., Galatius, A., Pund, R., Czeck, R., Jess, A., Siebert, U., & Körber, P. (2017). *Wadden Sea Quality Status Report Marine mammals*. 29.

Joint Nature Conservation Committee (JNCC) (2017). JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys.

Kastelein, R. A., Steen, N., de Jong, C., Wensveen, P. J., & Verboom, W. C. (2011). *Effect of broadband-noise masking on the behavioral response of a harbor porpoise (Phocoena phocoena) to 1-s duration 6–7 kHz sonar up-sweeps. The Journal of the Acoustical Society of America*, *129*(4), 2307–2315.

Løkkeborg, S., Ona, E., Vold, A., & Salthaug, A. (2012a). Sounds from seismic air guns: gear-and species-specific effects on catch rates and fish distribution. *Canadian Journal of Fisheries and Aquatic Sciences*, 69(8), 1278-1291.

Løkkeborg, S., Ona, E., Vold, A., & Salthaug, A. (2012b). Effects of sounds from seismic air guns on fish behavior and catch rates*. The effects of noise on aquatic life* (pp. 415-419). Springer, New York, NY.

Lucke, K., Siebert, U., Lepper, P. A., & Blanchet, M.-A. (2009). Temporary shift in masked hearing thresholds in a harbor porpoise (Phocoena phocoena) after exposure to seismic airgun stimuli. *The Journal of the Acoustical Society of America*, *125*(6), 4060–4070.

Ministry of Agriculture, Nature and Food Quality (2020). Updated Conservation Plan for the Harbour Porpoise Phocoena phocoena in the Netherlands: maintaining a Favourable Conservation Status.

Oestman, R., Buehler, D., Reyff, J., & Rodkin, R. (2009). Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish (p. 298). California Department of Transportation.

OFL (2020). Het Akkoord voor de Noordzee.

Popper, A. N., & Hawkins, A. D. (2019). An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. *Journal of Fish Biology*, *94*(5), 692–713.

Popper, A. N., Hawkins, A. D., Sand, O., & Sisneros, J. A. (2019). Examining the hearing abilities of fishes. *The Journal of the Acoustical Society of America*, *146*(2), 948–955.

Rako-Gospić, N., & Picciulin, M. (2019). Chapter 20 - Underwater Noise: Sources and Effects on Marine Life. In C. Sheppard (Ed.), *World Seas: An Environmental Evaluation (Second Edition)* (pp. 367–389). Academic Press.

Romijn, G. en G. Renes (2013), *Algemene leidraad voor maatschappelijke kosten-batenanalyse*, Den Haag: CPB/PBL.

Sarnocińska, J., Teilmann, J., Balle, J. D., van Beest, F. M., Delefosse, M., & Tougaard, J. (2020a). *Harbor Porpoise (Phocoena phocoena) Reaction to a 3D Seismic Airgun Survey in the North Sea*. *Frontiers in Marine Science*, *6*.

Seismic survey code of conduct (2020, June 15). Retrieved from: https://www.doc.govt.nz/our-work/seismic-surveys-code-of-conduct/code-of-conduct-for-minimising-acoustic-disturbance-to-marine-mammals-from-seismic-survey-operations/

Sierra-Flores R, Atack T, Migaud H, Davie A (2015) Stress response to anthropogenic noise in Atlantic cod Gadus morhua L. *Aquac Eng* 67:67–76.

Skalski, J.R., Pearson, W.H., & Malme, C.I. (1992). Effects of sounds from a geophysical survey device on catch-per-unit effort in a hook-and-line fishery for Rockfish (Sebastes). *Can J Fish Aquat Sci.* 49:1357-1365.

Soudijn, F. H., van Kooten, T., Slabbekoorn, H., & de Roos, A. M. (2020). Population-level effects of acoustic disturbance in Atlantic cod: A size-structured analysis based on energy budgets. *Proceedings of the Royal Society B: Biological Sciences*, *287*(1929), 20200490.

Sound of Marine Life (2020, June 15). Retrieved from: https://www.iogp.org/sound-and-marine-life-jip/

Southall, B., Finneran, J., Reichmuth, C., Nachtigall, P., Ketten, D., Bowles, A., Ellison, W., Nowacek, D., & Tyack, P. (2019). Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals*, *45*, 125–232.

van der Graaf, A. J., Ainslie, M. A., André, M., Brensing, K., Dalen, J., Dekeling, R. P. A., Robinson, S., Tasker, M. L., Thomsen, F., & Werner, S. (2012). *European Marine Strategy Framework Directive Good Environmental Status (MSFD-GES): Report of the Technical Subgroup on Underwater Noise and other forms of energy.*

van Oostveen, M., Sierdsma, F., Kwakkel, J., & van Mastrigt, A. (2018). *Inventory and assessment of models and methods used for describing, quantifying and assessing cumulative effects of offshore wind farms* (WATBF8129R001F1.0). Royal HaskoningDHV.

Vergeer, R., Blom, M. J., & Croezen, H.J. (2015). *Maatschappelijke effecten van alternatieven voor gasproductie uit het Groningenveld* (15.7G47.83). CE Delft.

Versteeg, S., von Benda-Beckmann, S., Geelhoed, S., Kinneging, N., van Kuijk, B. & Scheidat, M. (2020). *Assesment Methodology for Impulse Noise: A case study on three species*. Rijkswaterstaat: Ministry of Infrastructure and Water Management. D100141710:28.

WoodMacKenzie to Financieel Dagblad, as cited in Energeia article, “Hoe de gaswinning op de Noordzee steeds dieper wegzakt” (16th August 2019). Retrieved from: https://energeia.nl/fd-artikel/40083840/hoe-de-gaswinning-op-de-noordzee-steeds-dieper-wegzakt

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A1 Underwater noise effect on marine species

A1.1 Marine Mammals

Studies on effects of underwater noise on marine species identified different levels of noise impact. Noise can affect animals from a low level, at which it is heard but doesn't lead to a reaction, to a more extreme level, at which it physically damages the animals or even causes death. Van der Graaf (2012) has divided the effects of underwater noise on marine mammals according to sound pressure and frequency in different categories. The division is for all animals the same, only the limit depends on the species and the situation:

- Hearing zone: all noise that can be heard by an individual. Background noise and the sensitivity of the hearing apparatus are important. All noises, even those at which animals do not react are included in this category.
- Reaction: this is every noise for which animals show a reaction in their behaviour. Reactions can be small (distraction) or (curious) animals can be attracted to noise. The strongest reaction is that the animals leave the area. Also a (severe) discomfort zone (see below) is part of this category.
- Masking: Masking occurs when anthropogenic noise interferes with the sounds produced by animals (comparable in frequency and noise amplitude), or those of their prey or predators. Hereby communication or foraging skills can be disturbed.
- Hearing damage: occurs when the noise is so strong that temporary threshold shift (TTS) or permanent threshold shift (PTS) can occur, causing hearing damage of marine mammals. The spectrum of the noise levels is important for this category.
- Other physical or physiological damage or death: these are noises that are so strong that irreversible damage occurs of organs other than the hearing apparatus and that can disturb functions or even lead to death.

Impulsive noise

Studies have shown that marine mammals are the most sensitive to underwater noise produced by impulsive sound compared to any other marine species. There are various marine mammals such as minke whales, bottlenose dolphins and white-sided dolphins that can be found occasionally in the Dutch North Sea (van der Akker & Veen, 2013). However, the most frequent occurring marine mammals on the DCS include the harbour porpoise, harbour seal and grey seal. In this study we focus on the harbour porpoise and harbour seal.

Marine mammals can be classified in different categories based on noise sensitivity for impulsive noise. Southall (2007) identifies three categories: low frequency, medium frequency and high frequency hearing marine mammals. Harbour porpoises and seals belong to the group of cetaceans which are considered "high frequency mammals" meaning that these species are mostly sensitive to high frequency sounds.

Noise impacts such as disturbance, damage and masking can impact individual, as well as populations. The ecological effects are different depending on the type of noise produced. For impulsive sound, it is thought that the effect on communication is low because the energy produced by airguns and pile driving reduces significantly at high frequencies (those used for echolocation) and thus probably not lead to interference between and negative effects of marine mammals. However, the actual effects are greatly still unknown and impulsive noise can still have large effects on behaviour (avoidance) and even damage or death when the sound source is at close range.

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Harbour porpoise

Hearing

The harbour porpoise has a large frequency range from 200 Hz to 180 kHz (Southall et al., 2009). The frequency range is demonstrated by the harbour porpoise audiogram shown in the Figure A1. The harbour porpoise uses high frequency noise for echolocation. Additionally, this species depends on sound for communication and reproduction.

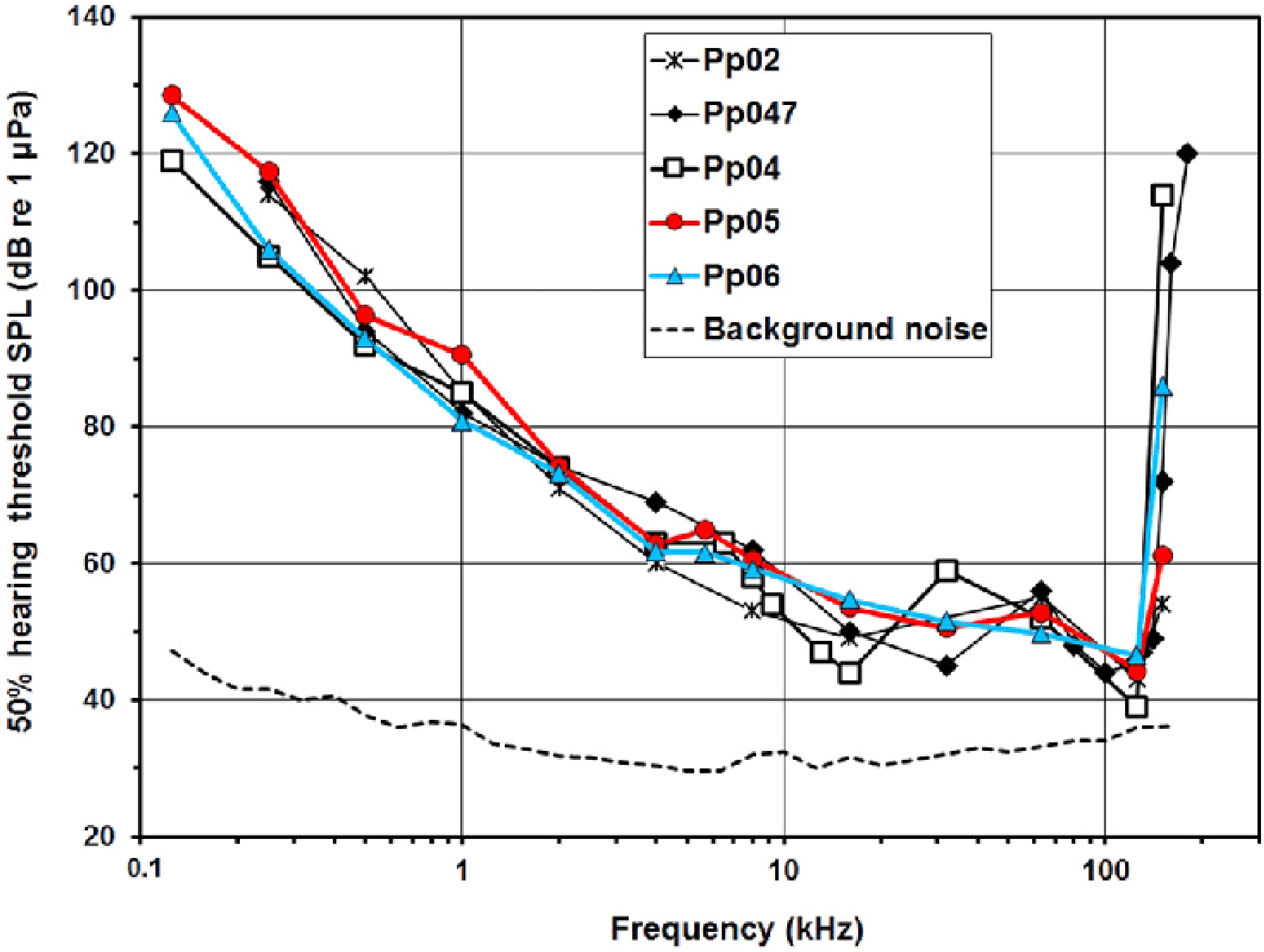

Figure A1 (Color online) The mean 50% hearing thresholds of the 6-yr-old female (porpoise Pp05) and 3-yr-old male (porpoise Pp06) harbor porpoise. Also shown are the audiograms of three young male harbour porpoises [porpoise Pp047, Kastelein et al., 2002; porpoise Pp02; Kastelein et al., 2010; porpoise Pp04; Kastelein et al., 2015]. The dashed line gives an indication of the average recorded background noise during the study which was dominated by electronic noise at frequencies above 3 kHz.

When sound levels exceed the hearing threshold, depending on the intensity level, it can cause avoidance, TTS and even PTS shift. The SEL at which these levels of disturbance occur are shown in the table A1.

Table A1 Calculated threshold values that have a certain impact on harbour porpoises, harbour seal sand fish. Sound exposure level (SEL) is proportional to the total energy of a signal expressed in dB re 1 μPa2 s. Source Southall, 2007. SEL1 = noise level of one single strike; SELcum = noise level perceived by a marine mammal after pile driving activity of one pile thus multiple strikes; SEL1 + cum,w = M-weighted SEL for seals in water, see Southal et al. (2019)

Species	Type of effect	Threshold value	Literature
Harbour porpoise	Avoidance	SEL_1 > 140 dB re 1 μPa²s/ 136 dB re 1 μPa²s	(Kastelein *et al*., 2011)
	TTS-onset	SEL_{cum} > 164 dB re 1 μPa²s	(Lucke *et al*., 2009)
	TTS-1 hour	SEL_{cum} > 169 dB re 1 μPa²s	TTS-onset + 5 dB
	PTS-onset	SEL_{cum} > 170 dB re 1 μPa²s	TTS-onset + 15 dB
Harbour seal	Avoidance	$SEL_{1,w}$ > 145 dB re 1 μPa²s	(Kastelein *et al*., 2011)
	TTS-onset	$SEL_{cum,w}$ > 171 dB re 1 μPa²s	PTS-onset – 15 dB
	TTS-1 hour	$SEL_{cum,w}$ > 176 dB re 1 μPa²s	TTS-onset + 5 dB
	PTS-onset	$SEL_{cum,w}$ > 186 dB re 1 μPa²s	(Southall *et al*., 2019)
Large Fish*	TTS-onset	SEL > 187 dB re 1 μPa²s	(Oestman *et al*., 2009)
Small Fish (< 2 gram)*	TTS-onset	SEL > 183 dB re 1 μPa²s	(Oestman *et al*., 2009)

*Research shows that fish are less sensitive to underwater noise than Oestman *et al*. (2009) suggested (Halvorsen *et al*., 2012a; Halvorsen *et al*., 2012b).

In the report of de Haan *et al*. (2015) an overview is given of the potential effects of seismic surveys on the harbour porpoise based on studies derived from explosions and pile driving. For an overview of the main potential effects of the (impulsive) underwater sound to the harbour porpoise we refer the reader to de Haan *et al*. (2015). Regarding the effects on the harbour porpoise caused by seismic surveys they concluded that:

- The most important factors determining a porpoise's reaction are the sound level above the hearing thresholds, the so-called sensation level, the stimulus duration and repetition rate. The effect these factors have depends on the context of the exposure: distance to the sound source, the animal's status, feeding condition etc.
- Given the characteristics of sounds emissions it seems unlikely that seismic surveys will cause primary blast injury on harbour porpoises.
- Sound exposure experiments established thresholds for TTS onset and growth to estimate the risk of PTS. This knowledge is attained from impulsive sound sources (either a single airgun, or intermittent playbacks of pile driving noise). However, different exposure stimuli lead to very different SEL onset thresholds. Therefore, the current TTS thresholds cannot directly be translated to seismic surveys, since the sounds characteristics of airguns differ from the studied sound sources.
- Observations in the field showed avoidance i.c. a decrease in the density of harbour porpoises for smaller airgun arrays (490 inch3), as well as a reduction in feeding activity, in a radius of 10 km in the North Sea. For large arrays (4820-6712 inch3) avoidance responses may occur even up to 70 km in deeper water in British Columbia. However, response levels and consequently response ranges vary with the context of the exposure (e.g. distance to source, behavioural state, importance of habitat), which makes it hard to translate these results to larger seismic operations occurring on the DCS.

Vulnerable period of the harbour porpoise

The harbour porpoise occurs year round in low densities ranging from 0.41 – 2.5 individuals per square kilometer in the Dutch North Sea. Figure A2 is an example of the harbour porpoise distribution in the North Sea. In previous years a higher abundance was observed during the spring and summer on the DCS. However, observations from recent years show a more equal distribution throughout the year (Geelhoed & Scheidat, 2018b; Gilles *et al*., 2016). During certain periods harbour porpoises are more vulnerable to disturbance than others such as in May, June and July the harbour porpoise young are born and nursed in areas north-east of the Dutch Wadden Islands. There are indications that they also are present along the Dutch coast. Underwater noise is enhancing the chance that mothers and calves are being separated from each other.

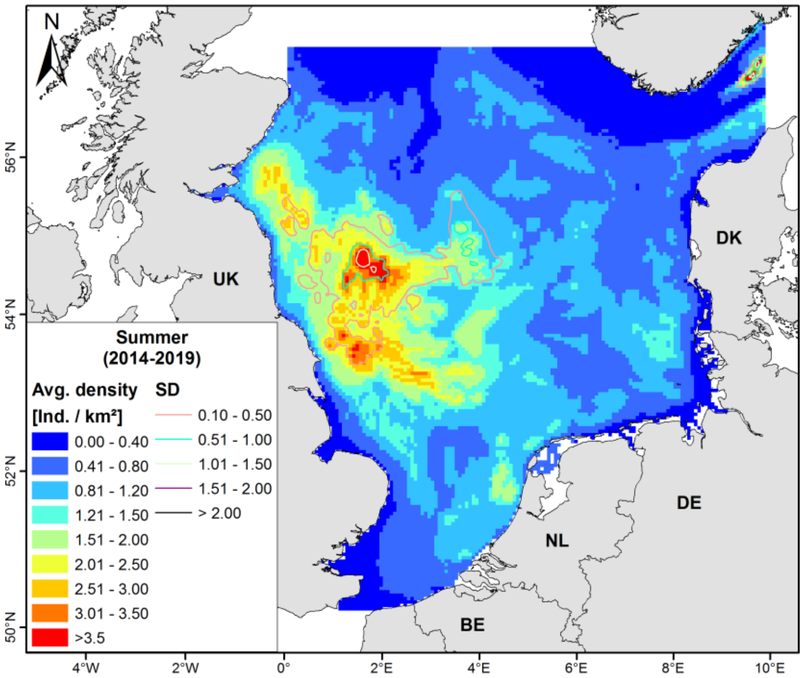

Figure A2 Harbour porpoise density distribution in the Dutch North Sea.

Harbour seal

Hearing

Seals are pinnipeds and have a different and smaller frequency range compared to harbour porpoises, but are also considered to be considered to be high frequency marine mammals. Their hearing frequency ranges from 75 Hz till 75 kHz. Figure A3 shows an audiogram for harbour seals demonstrating their frequency range and sound threshold. This is a slightly smaller range compared to harbour porpoises and they are less capable of hearing very high frequency sounds. There are studies that also show that seals are less vulnerable to underwater noise than harbour porpoises (Kastelein *et al*. 2011). The noise threshold levels for avoidance and TTS- and PTS onset result in higher sound exposure levels for seals (see figure A3).

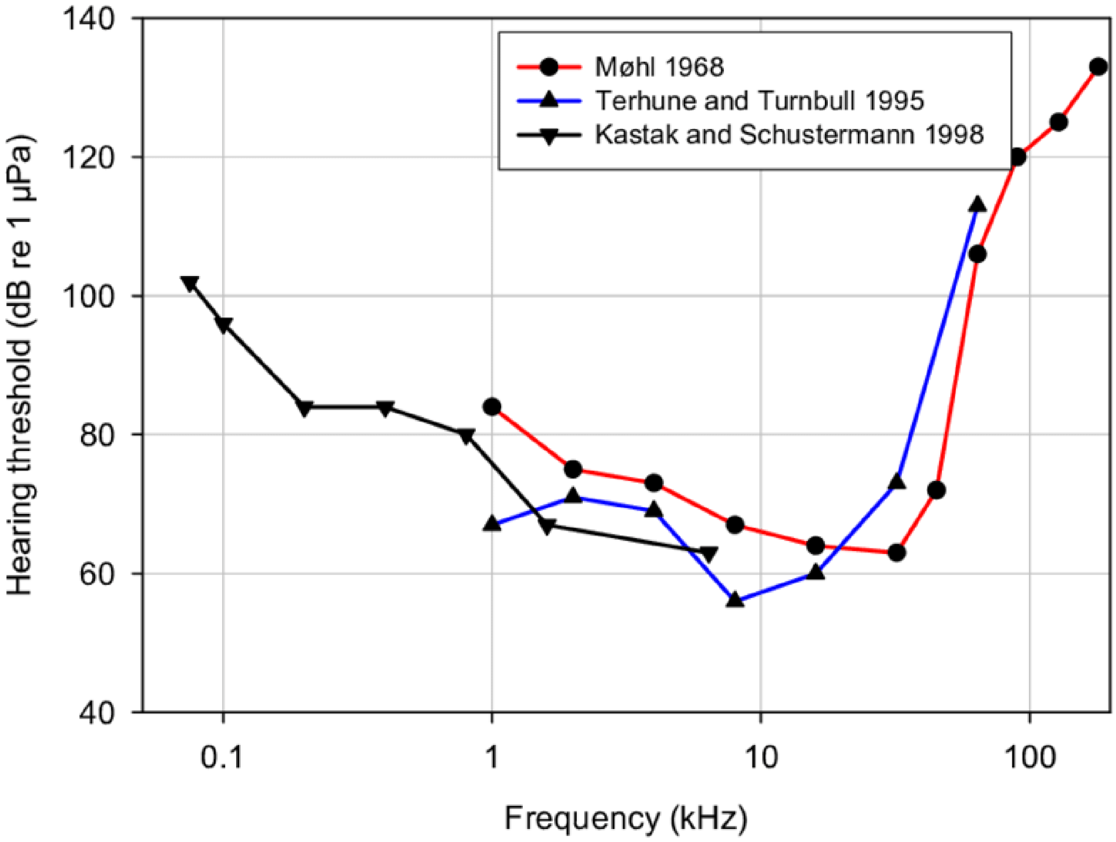

Figure A3 audiogram for harbour seals demonstrating their frequency range and sound threshold.

Vulnerable period seals

The harbour seal is present along the Dutch coast throughout the year. The harbour seal is widely distributed along the coast of the Dutch North Sea. During the winter months (December – February) the seals tend to use areas further offshore. During spring and summer months the seals tend to stay closer to shore due to moulting of the fur and reproduction (Figure A),(Aarts *et al*., 2016). The harbour seal is mainly observed in the Dutch coastal waters and makes short travels to forage. During certain periods and certain life stages harbour seals are more vulnerable to disturbance than other periods:

- The period of birth and nursing for the harbour seal is from May through July.
- The moulting period for the harbour seal is in August.

In the past the population of harbour seals was severely declined by hunting and pollution. In 1975 only 5410 individuals remained in the Wadden Sea. This led to a ban on hunting, which gave the harbour seal population the chance to recover. Over the past 45 years the population of the harbour seal has steadily increased. The rapid population declines visible in the data can be explained by virus epidemics (Jensen *et al*., 2017).

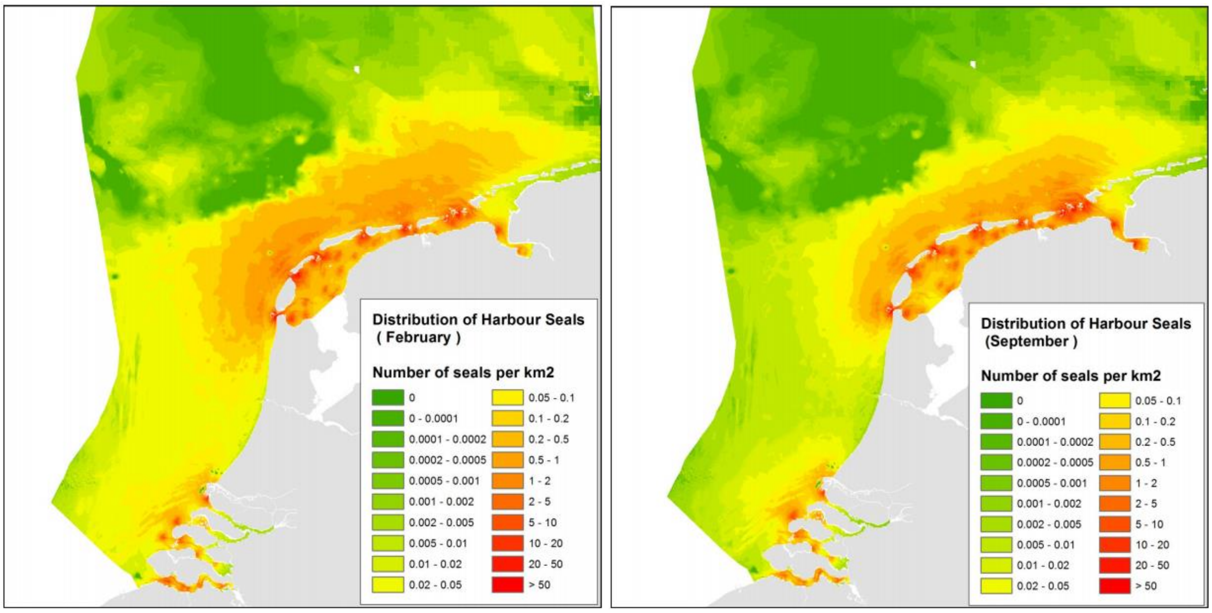

Figure A4 Harbour seal distribution in the Dutch North Sea (Aarts et al., 2016)

A1.2 Fish

Physical and physiological effects on fish from impulsive sound include permanent damage of the swimming bladder, blood vessel and hearing damage. Fish eggs and fish larvae can also be affected by underwater noise with a high sound level (mainly from impulsive sound). The eggs are in a planktonic stage and cannot swim and thus fish eggs cannot escape from high intensity noise. This makes fish larvae and fish eggs vulnerable for impulsive noise (van Damme *et al*., 2011).

Hearing

According to Popper *et al.* (2003) there are hearing generalists or specialists. Hearing generalists are fishes with no or a reduced swim bladder, with the sound sensitivity related to particle motion, detect sounds up to around 1 kHz and have a low auditory sensitivity (Popper *et al*. 2014). Hearing specialists are fishes with swim bladder and in some cases connected to the inner ear by the bullae (Figure A). Therefor these fishes are more sensitive to sound than hearing generalists and have a hearing range of sounds above 1.5 kHz (Popper *et al*. 2014). In Figure A5 an audiogram is shown of hearing generalists (sole) and specialists (cod and herring). For more detailed information on the hearing ability in fish we refer the reader to recent overviews on this topic (Popper *et al*., 2019; Popper & Hawkins, 2019).

Oestman *et al*. (2009) suggested TTS for larger fish occurs at SEL 187 dB re µPa2 s and for smaller fish (< 2 gram) occurs at 183 dB re µPa2 s. However, more recent studies show that fish are less sensitive to underwater noise than Oestman *et al.* (2009) suggested. Halvorsen *et al*. (2012a and b) stated that in some cases adult fish exposed to high intensity noise levels of 216 dB re 1µPa2 s do not show any physical damage. Bolle *et al* (2012) studied the impact of pile driving on common sole larvae and also concluded that a threshold value of 183 dB re 1 µPa^{2}s for TTS is too conservative. Thus, more recent knowledge (Bolle *et al*., 2012 and Halvorsen *et al* 2012) shows that the impact on initial mortality of fish, fish eggs and fish larvae is less than initially expected.

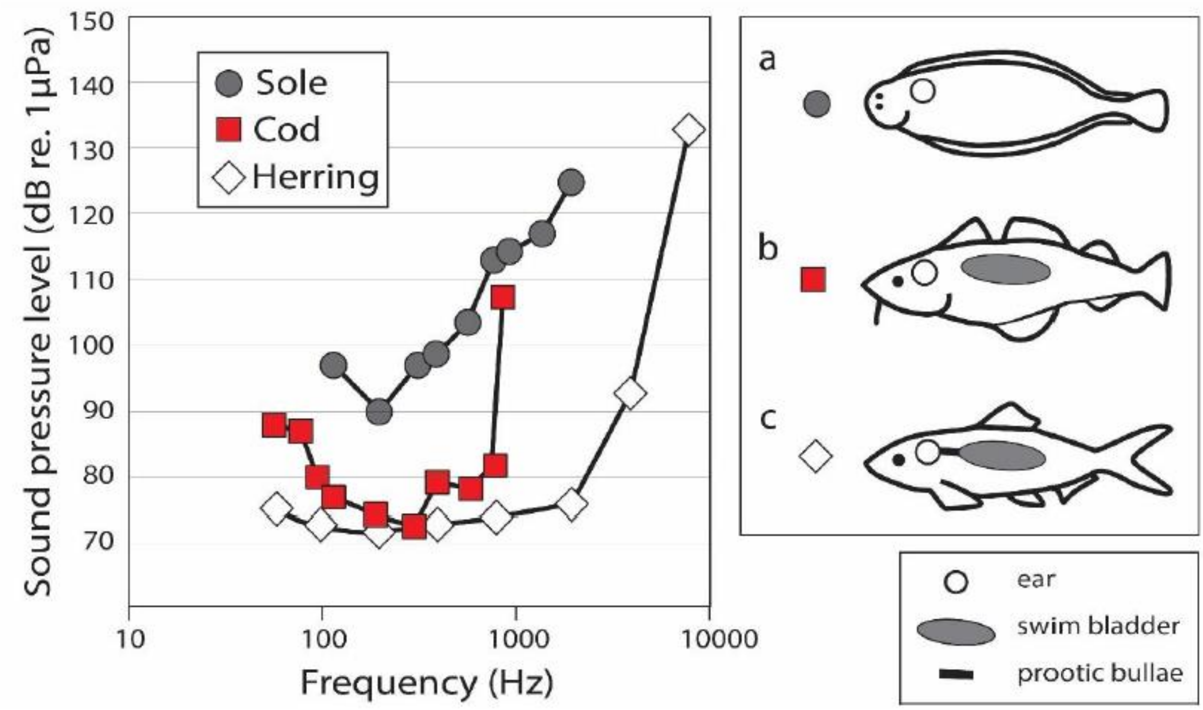

Figure A5 Overview hearing ability of sole, cod and herring and a schematic representation of the hearing systems. The sound pressure level (SPL) indicates the auditory sensitivity for a specific frequency, higher SPL indicating lower sensitivity. Sole has no swim bladder as an adult (a), cod has a swim bladder that is not connected to the ear (b) and herring has a connection between the swim bladder and the ear (c).

Vulnerable periods fish (eggs and larvae)

The fish eggs and fish larvae are not distributed equally during the year. The concentration of fish larvae in the North Sea is highest in December until May for plaice, January until May for herring and March until June for sole (Bolle *et al*., 2011). Also, the fish eggs and fish larvae of small sand eel and sprat are common in December until May. Therefore, the effects of impulsive noise on fish eggs and fish larvae have more consequences on the population during these months. Fish larvae and fish eggs are adversely affected by underwater noise and this leads to lower recruitment and food availability for other species in the food chain.

Atlantic cod

Atlantic cod is distributed quite equally over the entire North Sea and occurs in low population percentages in the Dutch North Sea.

A2 Seismic survey techniques[18]

Towed streamer data acquisition

All seismic surveys involve a source to generate sound waves and some configuration of receivers or sensors to record the reflected sound waves. Towed streamer operations represent the most significant commercial activity, followed by ocean bottom seismic surveys. In both cases, the sound waves are generated by airguns with compressed air. For the towed streamer operations the hydrophones are placed in streamers (a cable containing the hydrophone) which is towed or 'streamed' behind a moving survey vessel. These streamers are typically 3 to 8 kilometres long. For 2D surveys generally one airgun array and one streamer is deployed, for 3D surveys generally two airgun arrays and multiple streamers (6 - 8) are deployed.
During ocean bottom surveys, typically the receiver system are located in nodes or cables at or below the seafloor.

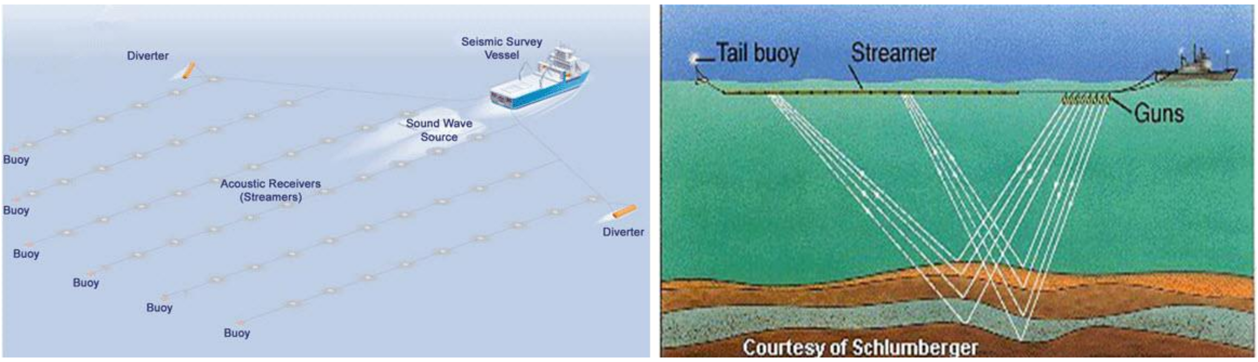

Figure A6 Seismic vessel with two seismic sources and six streamers (https://confluence.qps.nl/qinsy/latest/en/2d-and-3d-towed-streamer-seismic-surveys-182618953.html).

After firing the airgun, the strength and frequency profile of the sound wave alters by various processes. First, the strength of the signal diminishes because the signal is being spread over a larger volume as it moves away from the source (geometrical spreading). Secondly, the strength diminishes due to friction in the earth (absorption). Next, its frequency content decreases as absorption varies with increasing frequency).

[18] *The text of this section is derived from several information sources including IOGP and IAGC (in particular IOGP report no: 448 An overview of marine seismic operations, IOGP and IAGC, April 2011*

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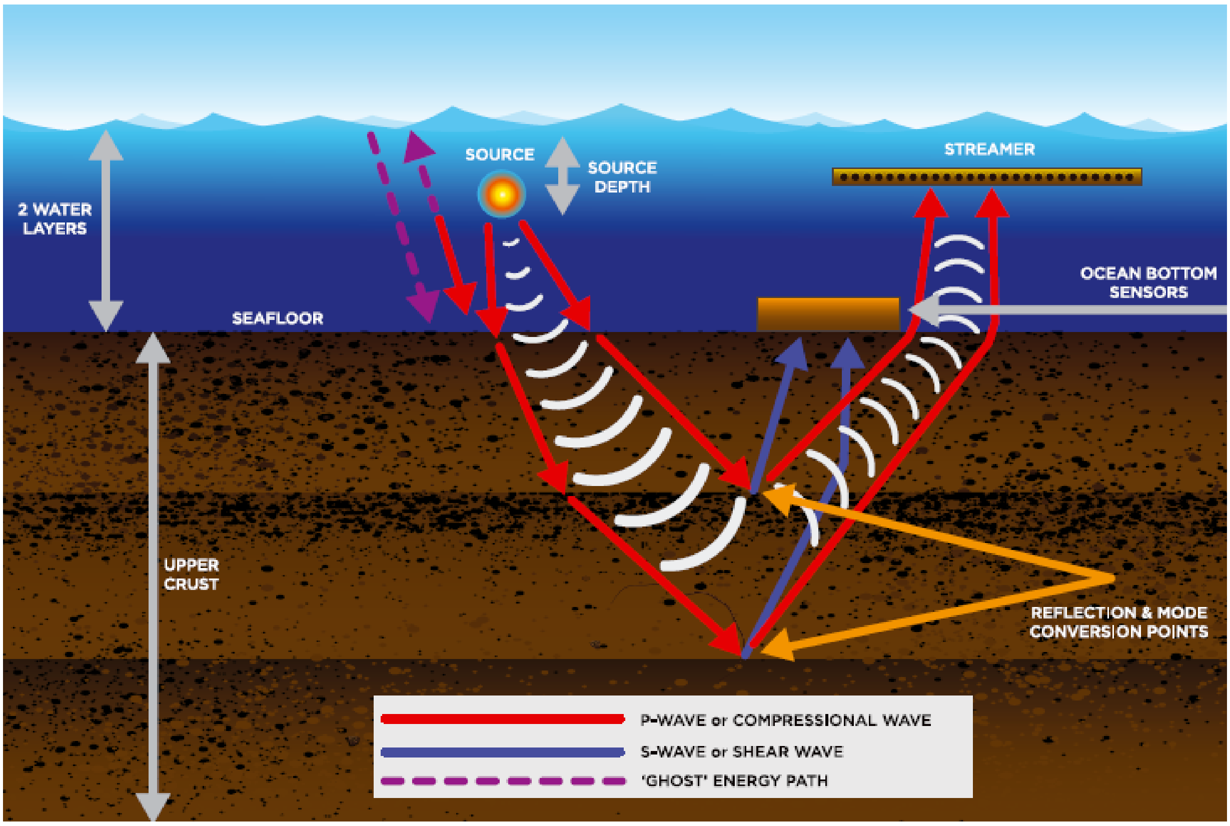

Figure A7 Sound waves in seismic surveys (source IOGP report no: 448)

For 3D surveys, the area of interest is investigated by sailing parallel sail lines. The sail lines are normally 400 to 800 meters apart from each other. Other patterns are also possible. A small 3D survey size is on the order of 300 square kilometres, or 1 000 sail line kilometres. A larger 3D survey may cover 1 000 to 3 000 square kilometres. Large seismic surveys may have a duration of several months to complete.

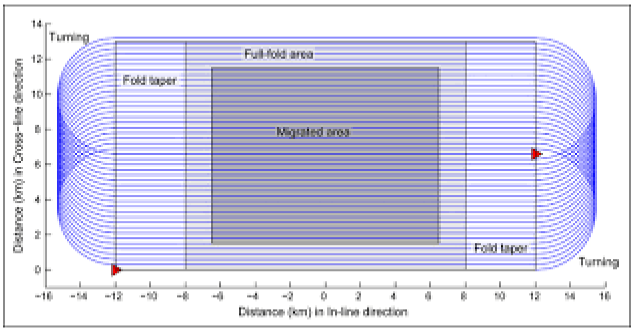

Figure A8 ‘Race track‘ sail line pattern in 3D seismic surveys (https://www.whoi.edu/cms/files/2009EO420002_71165.pdf)

Ocean bottom seismic techniques

During ocean bottom seismic techniques sound waves are also produced by a vessel that tows an airgun array through the water. However, the sensors to record the reflected sound waves are not located in streamers but lay on the seafloor or may even be buried in the top layer of the seabed. The sensors at the seabed can be contained in sensor cables or in sensor nodes (Ocean Bottom Nodes - OBN). Because the sensors lay on the sea floor, they can not only detect the reflected sound waves, but can also detect the direction thereof. This gives a more detailed image of the deep underground than what can be acquired with towed streamers. To detect the direction, various types of sensors are deployed. Basically, three principal types of seabed recording systems used in marine seismic: Ocean Bottom Seismometers (OBS), Two-Component (2C consisting of a geophone or accelerometer plus a hydrophone), and Four-Component (4C consisting of a three-component ground motion sensor in addition to a hydrophone). The data of the ocean bottom receivers can be used to generate 2D, 3D or 4D images of the subsurface.

Ocean Bottom surveys (especially 4C surveys) are more expensive compared to towed streamers because of the additional vessels and equipment that should be deployed. There are two principal objectives for 4C surveys: improved imaging of the subsurface and/or increased understanding of reservoir lithologies. For both the information of the direction of the sound wave is required. Another, advantage of ocean bottom system is that they can be deployed in shallow water. When streamers are deployed in shallow water the risk exists that they can get damaged when they touch the ground.

Based on data from an interview OBN surveys are more expensive and more time consuming. However, this highly depends on the survey design. As a very general rule of thumb OBN surveys will cost 6 – 8 times more than a towed streamer survey per km^2 and towed streamer surveys will be about ten times faster than OBN surveys.

Theoretically, there is no minimum (economical) size of the area that must be surveyed. However, in practice rarely towed streamer surveys of less than 200 km^2 are acquired. For OBN survey this is < 100 km^2. An exception is 4D seismic surveys, which can be quite small, because 4D is used to investigate the development of a specific oil or gas reservoir in time.

Bandwidth-Controlled Seismic Sound Source

The industry has developed Bandwidth-Controlled Seismic Sound Sources. An example is the “eSource”, a product of Teledyne Bolt. The eSource was developed with the aim to minimize sound in the frequencies for which the cetaceans are most sensitive, while still providing the seismic bandwidth adequate for survey operations. Higher frequencies (i.e. > 120 Hz) are not used for seismic imaging but do have an effect on marine life. Basically, the eSource is a redesign of the conventional airgun to exert greater control over acoustic spectral emissions. The eSource is also designed to be a drop-in replacement for current sources.

Technically, the eSource was principally optimised compared to conventional air guns by two improvements. In the first, exit ports which expel air into the water and produce acoustic energy are specially designed using computer fluid models to limit higher frequency content during actuation of the airgun. Secondly, the internal airgun mechanism is designed to apply greater control to the quickly moving valve that releases air through the ports. The design achieves its target of up to 40 dB less spectral amplitude above 100 Hz, while maintaining the energy below 100Hz necessary for seismic exploration. Figure A9 Amplitude spectra of the eSource compared to conventional sources (courtesy: Teledyne Bolt)shows the amplitude spectra of the eSource compared to conventional airguns. The A, B and C refer to the different liners that can be used to tune the gun. Each gun comes with each of the 3 liners.

Figure A9 Amplitude spectra of the eSource compared to conventional sources (courtesy: Teledyne Bolt)

According to Teledyne, the eSource is fully commercially available and has been deployed at the North Sea. The eSource is somewhat more expensive than a standard airgun by about 3000 to 5000 dollar per gun (depends on quantity purchased). Experience seem to show that there are no other advantages or disadvantages connected to noise reduction measures, e.g. increased time to survey a certain area.

Marine vibrators

While airgun arrays produce impulsive soundwaves with a high energy content, marine vibrators produce sound waves of a long duration and a lower energy level. Marine vibrators are a long-known concept as an alternative for airguns but have not yet resulted in a commercially and technologically viable system that can compete with the signal quality and reliability of air guns. Because of the environmental impact of airguns, but also to overcome technological disadvantages of airguns (repeatability of the seismic signal and control of its frequency content), the industry is working on the further development of marine vibrators.

Marine vibrators aim to spread the pressure output over time thus creating a non-impulsive wave that is not as harmful to marine life. Marine vibrators generate sound waves of low or ultra-low frequencies (2 - 10 Hz) and/or low frequencies (10 – 100 Hz) by a rapid mechanical displacement of water, for instance by vibrating plates that emit a pressure wave within a certain bandwidth. Both the amount of energy released, and the direction of release can be controlled to a high degree. The aim of MV-sources to reduce SPL (sound pressure levels) and SEL (sound exposure level) to below the point where they fall below the harm thresholds for marine mammals. The direction of emission of MV-sources and can be achieved by having several different vibrating plates lined up and controlled in such a way that they would constructively interfere in the vertical direction, and destructively interfere in the radial direction. This is called directivity.

Marine vibrators have several advantages over airguns:

- The output of a MV-source is more manageable than that of the airgun and the generation of low-frequencies without bubble pulse contamination is an additional benefit;

- The sound levels generated in the ocean by this marine vibrator are much lower than those of air guns, which means that their potential impact on marine species will be lower too. This reduction in sound impact is due to the reduced sound pressure levels (SPL) and sound exposure levels (SEL) associated with the signal emission. The aim is to keep the SPL and SEL below harmful levels;
- Lower sound pressure: unlike air guns, the marine vibrator is a non-impulsive source. Rather than releasing the total energy necessary for imaging all at once, it distributes it over time. This lengthening of the signal emission (known as “sweep”) from a few milliseconds (air gun) to several seconds (marine vibrator) reduces the sound pressure level (SPL) and therefore the maximum pressure emitted by the source;
- Reduced frequency range: while the airgun emits all sound frequencies simultaneously, the marine vibrator emits only the frequency range required for imaging, eliminating all unnecessary frequencies above about 100 Hz. The sound exposure level to which marine animals near the seismic sources are subjected to is therefore lower. Another benefit is that it is possible to reach very low frequencies (2 − 6Hz) which is useful in several types of inversions.

The major disadvantage of marine vibrators is that they are still under development and cannot be considered yet as a proven technique. The further development of MV-sources is organised in the Marine Vibrator Joint Industry Project (MV-JIP), sponsored by Shell, Total and ExxonMobil.