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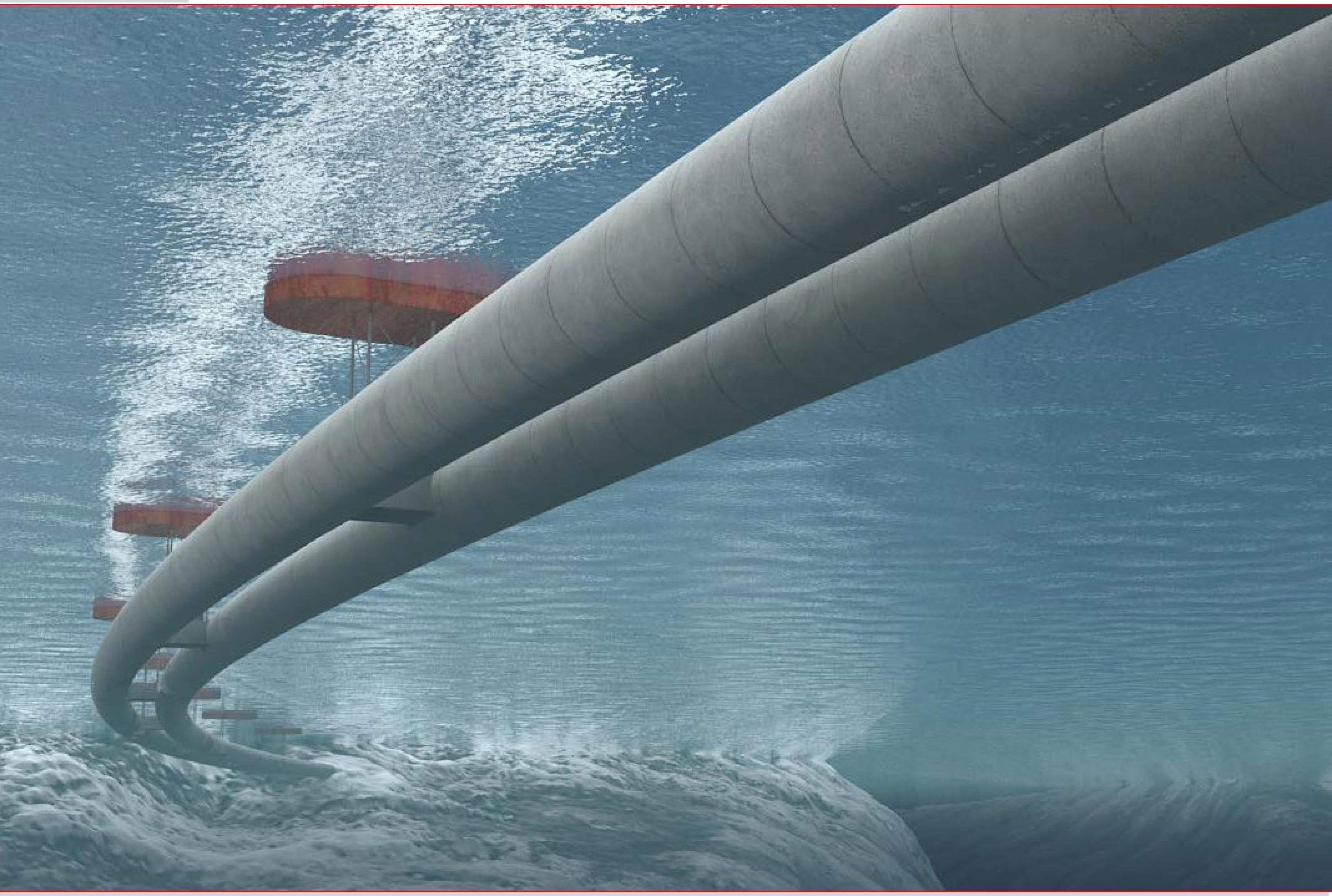
NINA Report

Environmental impacts of floating bridges

Arne Follestad, Johanna Järnegren, Evert Johannes Mul, Carolyn Rosten & Frode Thomassen Singsaas



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Submerged bridge © Statens Vegvesen

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Abstract

Follestad, A., Järnegren, J., Mul, E.J., Rosten, C. & Singsaas, F.T. 2022. Environmental impacts of floating bridges. NINA Report 2057. Norwegian Institute for Nature Research.

The Norwegian government has an ambition of better connecting the west coast of Norway between Kristiansand and Trondheim. Improvement of the fjord crossings will be the primary means of improving connections and reducing travel time. This project has been termed the Ferry Free E39 project and is the responsibility of the Norwegian Public Roads Administration (NPRA). Many of the fjord crossings on the west coast present difficulties for existing bridge and tunnel technologies due to the spans that need to be crossed, or the depths of the fjords. The NPRA is therefore scoping new solutions in the form of floating bridges and submerged, floating tube bridges (SFTB). Floating bridges and SFTB use new approaches such as suspension of bridges, or submerged tunnels, from pontoons. This enables deeper (over 400 m), or wider (over 2 km) stretches to be crossed.

When evaluating new technological solutions, it is important to consider their potential environmental footprints. For this reason, the NPRA has commissioned the Norwegian Institute for Nature Research (NINA) to evaluate the potential environmental effects of floating bridges and SFTB through literature study and expert evaluation. We applied a semi-systematic literature review approach and identified 195 potentially relevant publications. Since floating bridge technology is new and has, as of yet, rarely been applied in practice, little literature that directly assesses environmental effects of floating bridges is available. We addressed this by including literature from other anthropogenic structures in marine environments (e.g., offshore wind farms) which have met some of the same challenges during their construction or operation.

The literature review identified four main classes of environmental impact: habitat alterations, noise pollution, light pollution, and gateways to new ecosystems (e.g. islands) for predators. These impacts were discussed in depth with consideration for both aquatic (benthic invertebrates, zooplankton, fishes and marine mammals) and terrestrial (birds, mammals) organisms and communities. Since fjord crossings already exist in the form of ferries at all locations being considered for floating bridges, potential environmental impacts were compared to ferries, and not a null-crossing situation.

We then present our expert evaluation based upon findings from the literature review and the authors expertise. Two phases were considered during the expert evaluation, the construction phase and the operation phase, since these present different environment challenges. We identified the following groups of effects: (i) habitat changes in the form of reduction in habitat quality through avoidance or acoustic masking, and new habitat availability through additional physical structures for benthic organism growth or removal of barriers to island habitats for predators and other mammals; (ii) physical injury, specifically from noise produced during the construction phase; and (iii) barrier effects in the form of either physical barriers (e.g. SFTBs) or barriers to migration caused by noise, light, or hydrodynamics. Finally, we present mitigation possibilities to reduce the negative environmental impacts of floating bridges and SFTBs, and highlight some key future research needs in this novel and largely unexplored field.

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Sammendrag

Follestad, A., Järnegren, J., Mul, E.J., Rosten, C. & Singsaas, F.T. 2022. Miljøeffekter av flytende bruer. NINA Rapport 2057. Norsk institutt for naturforskning

Norske myndigheter har en ambisjon om en bedre veiforbindelse langs kysten mellom Kristiansand og Trondheim. Nye og bedre måter å krysse fjordene på vil være det beste virkemidlet for å redusere reisetiden. Prosjektet har blitt kalt ferjefri E39, der Statens vegvesen (SVV) er ansvarlig for prosjektet. Mange av fjordene på Vestlandet er for brede eller for dype til å bygge tradisjonelle broer eller tunneler. Prosjektet undersøker derfor konsekvensene av alternative løsninger i form av flytende broer. De kan ha forskjellig utforming, fra nedsenkbare tuneller som kan festes til bunn eller henge i pongtonger på overflaten, til flytebroer montert på pongtonger. Flytende broer kan være et alternativ for å krysse dype fjorder, der største dyp er fra 400 meter eller mer, og der fjorden er over to kilometer bred.

Ved vurdering av nye teknologiske løsninger er det viktig å ta hensyn til mulige miljøeffekter. Statens Vegvesen ga derfor NINA oppdraget med å vurdere mulige miljøeffekter av slike broløsninger gjennom et litteraturstudium og en ekspertvurdering. Vi utførte en semi-systematisk litteraturstudie og identifiserte 195 potensielt relevante publikasjoner. Siden teknologien bak flytende broer er ny, og foreløpig i liten grad tatt i bruk, finnes det lite litteratur som direkte tar for seg miljøeffekter av flytende broer. Vi løste problemet ved å inkludere litteratur fra liknende menneskeskapte strukturer i marine miljøer, som offshore vindmøller, som har hatt flere av de samme utfordringene knyttet til konstruksjon og drift.

Litteraturstudien indentifiserte fire hovedtyper av miljøpåvirkning: habitatendring, lydforurensing, lysforurensing, og inngangsporter til nye økosystemer (for eksempel øyer) for predatorer. Vi diskuterte disse påvirkningsfaktorene med hensyn til både vannlevende (bunndyr, dyreplankton, fisk og sjøpattedyr) og landlevende (fugler og pattedyr) arter og samfunn. Siden ferger allerede krysser fjorden på alle lokalitetene hvor flytende broer vurderes, har vi sammenliknet mulige miljøeffekter med ferger, og ikke uberørte områder uten trafikk over fjorden.

Vi presenter vår ekspertvurdering basert på funn i litteraturstudien og artikkelforfatternes ekspertise. Vurderingen ble gjennomført i to faser, konstruksjons- og driftsfase, siden disse medfører ulike miljømessige utfordringer. Vi delte miljøeffektene inn i følgende grupper: (i) habitatendringer i form av redusert kvalitet på eksisterende habitat, nye fysiske strukturer danner nye habitater eller fjerning av barrierer, (ii) fysiske skader, spesielt fra støy i konstruksjonsfasen og (iii) barriereeffekter i form av enten fysiske barrierer (for eksempel nedsenkbare tuneller) eller lyd- og lysbarrierer. Vi presenterer til slutt mulige avbøtende tiltak som kan redusere negative miljøpåvirkninger av flytende broer og nedsenkbare tuneller, og fremhever framtidige forskningsbehov i dette nye, og i stor grad uutforskede fagfeltet.

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Contents

Foreword

The Norwegian Public Roads Administration (NPRA) commissioned NINA to carry out a literature study and expert evaluation on the potential environmental effects of floating bridges, since they show much promise for providing fixed links particularly in deep and large fjord crossings. This report provides the basis needed to include environmental impact assessment early in the design process and may be used as a decision tool during the design phase.

The assignment for this project includes:

- Mapping of existing knowledge on how floating constructions may impact marine and terrestrial organisms and seabirds with focus on noise, vibrations (movements in the structure), presence of the construction and how it may change the surrounding environment.
- Perform an assessment of existing sources of noise connected to floating bridges related to traffic to make it possible to compare impacts of floating bridges and ferries.
- Obtain experience with other sources of noise, as sonars and seismic, and how these may impact biodiversity in the marine environment.
- Establish a basis for which measures and considerations should be made during the planning phase to facilitate appropriate mitigating measures and solutions to minimize environmental footprint of the structures.

From the literature search, a total of 195 relevant publications were identified as relevant for the present study. This report includes a broad range of references related to the potential effects that are associated with floating bridges. Although these references do not discuss floating bridges, they may be relevant in the evaluation of potential ecological effects.

12.01.2022 Arne Follestad

1 Introduction

1.1 Background

Examples of permanent floating bridges are relatively rare. Although the concept of floating bridges is not new, most designs have been used in non-permanent settings, often in the context of military activities. As a result, the body of scientific literature that specifically addresses ecological effects of floating bridge designs is almost non-existent. Despite the lack of literature, it is evident that floating bridges can alter habitats and affect species (see literature review in Ghanim et al. 2021, Moore et al. 2013). One strategy to evaluate how floating bridges may affect local ecosystems is to aggregate and review studies that addressed other anthropogenic structures in marine environments and use expert evaluation to extrapolate to floating bridges. For example, numerous studies have addressed the ecological effects of windfarms, pile-driving and other construction activities, aquaculture facilities, fisheries shipping, and pipelines (e.g. Lindeboom et al. 2011, Kuşku et al. 2018, Cox et al. 2018, Bray et al. 2016, Nabe-Nielsen et al. 2014, Fliessbach et al. 2019). Many of these ecosystem effects are likely to overlap with those that may be caused by floating bridges, either during the construction phase or during the operational phase. This report therefore consists of an extensive literature review and expert evaluation to identify potential environmental impacts from the construction and use of different floating bridge designs.

1.2 Plans for a ferry free E39

The plan for a ferry free E39 project aims to eliminate all ferries along the coastal highway E39 in Norway, from Stavanger to Trondheim. This route crosses several fjords which are characterized by great widths (up to 5 km) and depths (up to 1 km). Recent development of offshore technology has now made it possible to plan for new, non-conventional engineering solutions for crossing these fjords without ferries. Floating bridges, submerged floating tube bridges (SFTB) with pontoons or vertical tethers, and suspension bridges on tethers (TLP) have now become a possibility for such crossings. An SFTB will, when built, be the first of its kind worldwide (Source: NPRA).

The Norwegian Public Roads Administration (NPRA) has completed several scoping studies comparing different solutions for crossing the fjords along the E39. These solutions all have advantages and disadvantages, also related to environmental impacts. Up until now no specific literature has been available in their planning of bridges.

Better knowledge of the impacts of floating bridges is important to compare the different solutions and their potential impacts on species and ecosystems. Some of these evaluations will be specific to a geographic area, while others are of a more general nature and connected to the type of construction. General features can be used in the planning process of all fjord crossings, also for comparison to other types of infrastructures, like ferries and fixed bridges.

The NPRA wishes to understand how existing and new technology may impact the biological environment in the vicinity of a bridge, both above and below water surface, so that environmental considerations can be included in the planning process. This report outlines environmental perspectives that ought to be considered during the planning of floating, and traditional, bridges, to ensure environmental impacts are minimize and subsequent mitigation costs are reduced.

1.3 Floating bridges

1.3.1 Floating oversea bridge

A floating oversea bridge floats on pontoons. The structure has an open deck, connected with pillars to the pontoons. If the crossing must allow the boats to pass, a part of the deck is

Figure 1. Floating bridge crossing Bjørnafjorden (from Statens Vegvesen).

elevated, with the help of towers and cables (cable stayed bridge, **Figure 1**). Fillings near the shores or along the structure are usually evaluated as alternatives for the tower location or to shorten the length of the crossing.

Floating bridges are typically considered where undersea tunnels, or suspension bridges are not possible due to the distance of the crossing, or depth of the fjord. In these cases, fjord crossings with ferries are already established. It is important to highlight, that when a floating oversea bridge is a part of a solution to permit a physical fjord crossing, the environmental effects of the crossing solution should be evaluated as an alternative, and in comparison, to ferries.

1.3.2 Submerged floating tube bridge (SFTB).

The submerged floating tube bridge consists of submerged tubes floating under the water surface (**Figure 2**). These structures may have different cross-sections (one or several tubes, with connecting elements, of circular/rectangular/elliptical shape) and the bridge may have intermediate elements (pontoons, tethers, pillars), depending on the depth of the water and the length of the bridge. The tethers are the same elements as those used for TLPs.

Along the E39 road, there are some crossings that are very exposed to environmental loads. These crossings can also be too deep and wide to consider a traditional bridge, such as a suspension bridge, that can reach lengths of up to 2 km. In this case, a SFTB would be a competitive solution, because, submerged from the sea-surface, the structure naturally reduces the main loads with the depth.

When the SFTB is hanging in green pontoons (**Figure 3**), they may be attractive nesting places for some seabirds, such as gulls, terns, and oystercatchers, as these man-made islands are safe for mammalian predators.

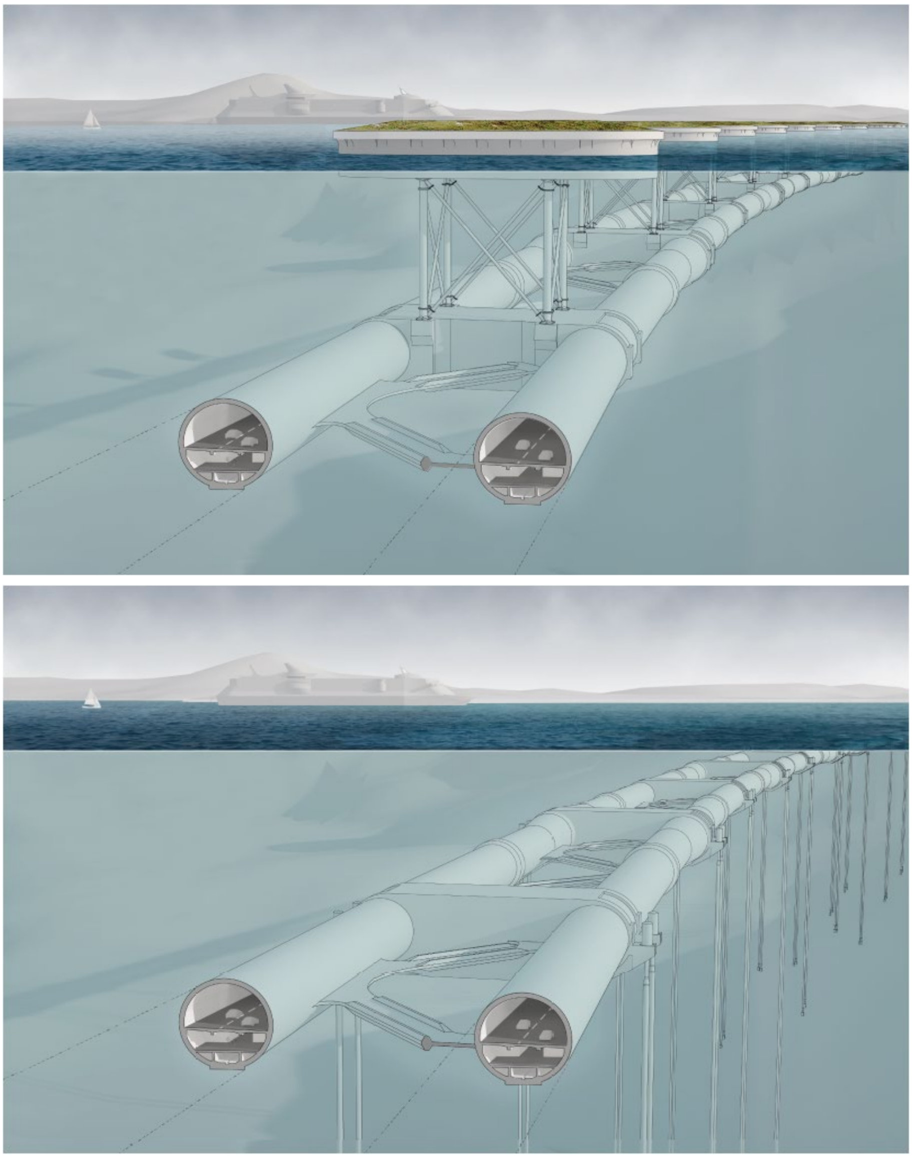

Figure 2. Submerged floating twin-tube bridge with floating pontoons (above) and tension legs to the bottom (below) (from Statens Vegvesen).

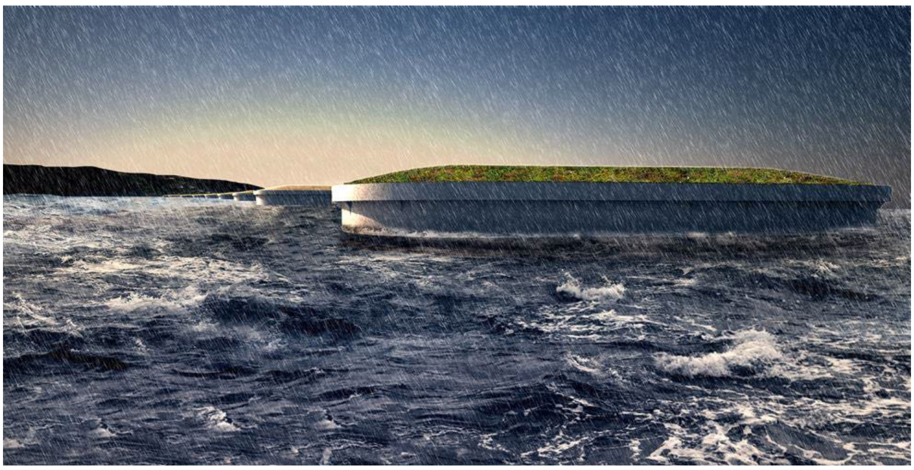

Figure 3. SFTB with green floating pontoons (from Statens Vegvesen).

1.3.3 Suspension bridge

The suspension bridge is a deck suspended on cables that are attached to towers (**Figure 4**). The structure is an oversea bridge, but for lengths more than approximately 2 km, intermediate towers must be provided. These towers can be ground-based, but for deep waters a solution of TLP (tethers) towers is an alternative (**Figure 5**).

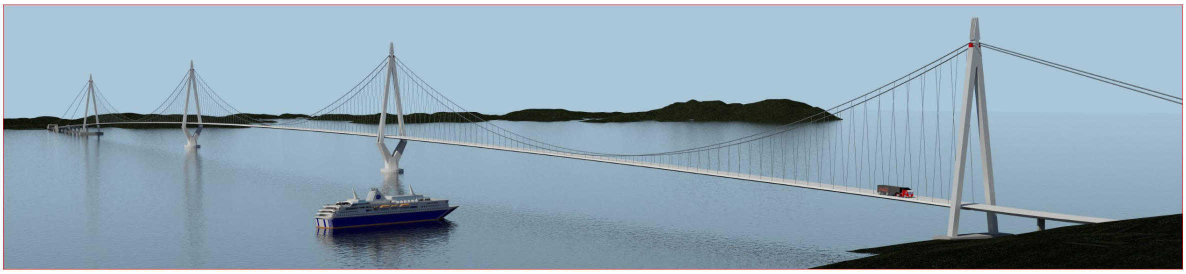

Figure 4. Suspension bridge on TLP for Bjørnafjord (from Statens Vegvesen).

Figure 5. Suspension bridge on TLP for Bjørnafjord – underwater view (from Statens Vegvesen).

1.4 Offshore wind turbines

Since so few floating bridges or SFTB have yet been built, or planned, evaluating their environmental footprint is challenging. One way around this problem is to use the experiences from other anthropogenic structures in marine environments. Offshore wind turbines utilise some of the same approaches as floating bridges, so evaluations of potential environmental impacts of these can provide valuable information and are therefore discussed below.

Expected Effects of Offshore Wind Farms

Biological effects resulting from the construction, and operation, of offshore wind farms (OWFs) were identified in a review of studies in Northern European Seas (Bray et al. 2016). Wind farms affect resident and migrating birds, through avoidance behavior, habitat displacement, and collision mortality. Parameters that are heavily weighted on the risks of collision mortality includes flight altitude, flight maneuverability, percentage of flight time, nocturnal flight altitude, disturbance by wind farm structures, ship and helicopter traffic, and habitat specialization. The risk of collision with OWFs is also related to the movement of the upper part of the installation and its dimensions. In the case of 'static', 'not-moving' bridge elements, this event is regarded as rarer.

When planning for OWFs several countries in Northern Europe and in the Mediterranean have identified potential OWF “hotspots”. In the Mediterranean, using lessons learned in Northern Europe (see Bradbury et al. 2014, Bray et al. 2016, Furness et al. 2013, Garthe & Huppop 2004) they have identified sensitive species and habitats that will likely be influenced by OWFs in both these hotspot areas and at a basin level. This information will be valuable to guide policy governing OWF development and will inform the industry when environmental impact assessments are required for the Mediterranean Sea.

In the breeding season, many seabird species can fly long distances (> 100 km) to find food for their chicks. If birds from colonies far from the planned sites for floating bridges find their food close to these sites, the possible occurrences of birds from colonies or breeding areas far from the site, must also be evaluated.

For fish, population- and community-level effects are poorly known, as available studies are typically short term or relate to individual fish species. Fish are expected to be affected by OWF in both positive and negative ways. A positive effect may occur due to the increased habitat complexity provided by the foundations and any additional scour protection structures. The introduced structures provide increased shelter and colonization substrates for many marine organisms, which in turn may also attract foraging species. This effect is also well known from other anthropogenic structures in the sea, such as oil platforms, piers, wrecks etc. Concerns have also been raised that fish may be repelled from OWF areas because of noise disturbance or disturbance from electromagnetic fields created around cables on the seafloor (references are given in Bergström et al. 2014, Bergström et al. 2013).

Surveillance studies at the Lillgrund wind farm in Sweden on benthic fish communities, revealed no large-scale effects on fish diversity and abundance after establishment of the wind farm when compared to the development in two reference areas. However, changes at smaller spatial scales were evident. Increased densities of all studied piscivores (cod, eel, shorthorn sculpin) were observed close to the foundations in the first years of operation. The increase was probably attributed mainly to local changes in distribution. These results give some indication that OWF might provide long-term benefits by enhancing local ecosystem services (Bergström et al. 2013). it is, however, difficult to say if bridges will have the same positive effect. The offshore windfarm foundations provide hard-substrate habitat for benthic species (etc.), which ultimately leads to increased fish density, but this is in areas where there is perhaps not much hard substrate habitat to begin with. The fjords along the E39 have plenty of hard-substrate habitat, so they will likely not have the same effect in such an environment. This speculation ought to be tested before drawing conclusions.

2 Methods

Traditional, qualitative literature reviews can sometimes represent subjective views, they can lack transparency, or they can be liable to biases. To avoid this, we based our literature search on some of the more systematic techniques known from search building in evidence reviews (Collins et al. 2015).

Some test searches were conducted, and then relevant search terms and synonyms were identified and sorted into three different categories:

- Terms related to floating bridges and other relevant constructions/vessels
- Terms related to impacts
- Terms related to animals and environment

The search terms were then put together using Boolean operators: OR between terms within the same category, and AND between different categories. In some cases the Boolean operator NEAR/* was used for further narrowing of certain terms.

The following search was conducted in Web of Science Core Collection on October 26th 2021:

(TS=(float NEAR/3 bridge*) OR TS=(discrete-pontoon) OR TS=(continuous-pontoon) OR TS=(pontoon-separated) OR TS=(subsea NEAR/3 tunnel*) OR TS=(underwater NEAR/3 tunnel*) OR TS=(submerged NEAR/3 tunnel) OR TS=(submerged NEAR/3 bridge) OR TS=(Suspend* NEAR/3 tunnel) OR TS=(Archimedes NEAR/3 bridge) OR TS=(Float* NEAR/3 structure*) OR TS=("wind turbine" AND (sea* OR offshore OR water)) OR TS=("wind power" AND (sea* OR offshore OR water)) OR TS=("wind farm" AND (sea* OR offshore OR water)) OR TS=((cable* OR cord* OR Rope*) AND (bottom OR seabed OR seafloor OR "ocean floor")) OR TS=(ferry OR ferries))*

AND

(TS=(pollution) OR TS=(nois*) OR TS=(light* AND (pollut* OR disturb*)) OR TS=(vibrat*) OR TS=(barrier*) OR TS=(current* AND (ocean OR sea OR river OR water)) OR TS=(collision*) OR TS=(temperat*) OR TS=(entangle*))*

AND

(TS=(Plant) OR TS=(animal*) OR TS=(seabird*) OR TS=(invertebrat*) OR TS=(whale*) OR TS=(fish*) OR TS=(seal*) OR TS=(mammal*) OR TS=(Bentho*) OR TS=(environment*))*

The search resulted in 1441 publications in Web of Science Core collection. As many of these references were not relevant for this review study, all 1441 references were subsequently evaluated using the reviewing tool “Rayyan” (www.rayyan.ai). The result list was split into four equal parts for screening, one part for each researcher in our team. All references were then screened, based on title and abstract. 1154 references were excluded from the study, while 161 references were deemed relevant by one evaluator in the first evaluation round. In addition, 126 references were initially marked as potentially relevant – from which 32 were eventually included based on the assessment of a second evaluator. The total list of publications that were deemed relevant thus consists of 195 publications.

Based on this list of relevant publications, a number of potential consequences of floating bridges were identified. Most of these consequences have been addressed in relation to other anthropogenic activities, even though these studies might not have been related directly to floating bridges. Whenever relevant, such publications have been used in this report to address the potential consequences of floating bridges in more detail. In addition, “grey literature” was searched for in Google, and some papers referred to in the examined publications were also included in the report.

3 Results

3.1 Existing literature on floating bridges

Few scientific studies (Ghanim et al. 2021, Moore et al. 2013) have directly addressed the impact of floating bridges on the surrounding ecosystem. However, our extensive automated literature search yielded 1441 references, from which 195 were deemed relevant after manual evaluation. Most of these studies did not directly evaluate ecological consequences of floating bridges, but they address elements that overlap with floating bridge designs and discuss associated ecological consequences.

3.2 Potential effects of floating bridges

Based on the assembled literature, the ecological consequences of floating bridges and other anthropogenic activities in the marine environment can be divided into different categories. These can be broadly summarised as habitat changes, noise, light, gateways and other considerations. These categories are addressed in the sections below.

3.2.1 Habitat change

Hydrodynamics
The physical presence of an artificial structure will alter local hydrodynamics around the structure, effecting currents, wave energy and flow. Depending on depth, this may influence sediment distribution, sediment properties and grain size which typically leads to changes in environmental diversity, abundance and species composition (Martin et al. 2005, Moschella et al. 2005, Walker et al. 2008). These changes are most pronounced in the immediate vicinity of the structure. Recent research suggests that a floating bridge may alter hydrodynamic patterns in a fjord (Khangaonkar et al. 2018a). Circulation in a classic fjord is characterised by a shallow brackish layer at the surface over a deep saltwater column that is vulnerable to disruptions. The presence of floating structures could constrict the mixing and transport in the upper layers (<20 m) of the water column (Khangaonkar et al. 2018b). In addition to currents, this may effect also salinity and temperature downstream of the construction (Khangaonkar et al. 2018a).

Artificial reefs
Research has shown that if a structure remains intact long enough to allow ecological succession, the dominating species on floating structures are filter feeders, such as tunicates, sponges, hydrozoans and polychaetes (Connell 2000, Perkol-Finkel et al. 2008, Vandendriessche et al. 2015, Whomersley & Picken 2003). However, artificial structures differ physically from natural habitats with respect to substratum composition, complexity, surface area, age, orientation, movement and disturbance regimes. It is shown to support different ecological communities compared to natural habitats, often characterised by greater abundances of opportunistic and non-native species. Surveys have shown that artificial structures favour non-indigenous species over native hard-bottom species (reviewed by Bishop et al. 2017, Momota & Hoskawa 2021). Opportunistic colonists of hard substrates are often tolerant to a wide range of environmental conditions and have larvae present in the water column for much of the year and are therefore able to rapidly recruit to new substrates. Artificial structures have played a role in establishment and spread of invasive algae (Bulleri & Airoldi 2005) and mussels (Baker et al. 2007, Spinuzzi et al. 2013) but also indigenous species (Rooker et al. 1997) and it may play a role in facilitating climate migrants (reviewed by Bishop et al. 2017). It is important to note that artificial floating structures do not have a natural counterpart, meaning that these structures create novel habitats for both benthic and pelagic organisms (Holloway & Connell 2002, Perkol-Finkel et al. 2006).

The biomass on a submerged artificial structure may reach up to 500-fold the biomass found in the surrounding soft sediment and mainly consists of filter-feeders (Picken et al. 2000). Through this it may act as a bio-filter, affecting the water chemistry and particle composition, and depleting primary organic matter in the close vicinity (<100 m) (Maar et al. 2009).

Floating structures offer a shaded habitat with overhang, something that is rare in natural marine habitats. These are habitats where invasive species often thrive, but here ecological engineering can play an important part by adding elements to lessen shading effects and include 3D complexity offering shelter for juvenile fish etc. (Hadary et al. 2022).

Another effect that has received little attention is the fact that organisms attached to floating structures live at a fixed depth and do not experience tidal cycles. This may effect behavioural patterns of benthic intertidal communities (Hadary et al. 2022). If this has any importance to these systems remains to be seen.

The anchor and connecting system of any artificial structure will destroy habitats on the ocean floor. It is important that this system is designed for minimal contact with the seabed to prevent erosion and destruction of valuable habitat. Concrete gravity based anchor or sinker have greater eco-engineering potential than mooring solutions, as they can be designed to provide habitat or shelter to the affected area (Hadary et al. 2022).

Migration barrier

Migratory species are more likely to encounter and be affected by anthropogenic barriers than non-migrating species. Studies indicate that a floating bridge may function as a barrier to salmonid fish passage. Slower migration times, higher mortality rates in the vicinity of the bridge relative to other areas on the migration route, and unique behaviour and mortality patterns at the bridge suggests they impede migration and increasing predation of salmonids (Celedonia et al. 2008, Moore et al. 2013). During early migration Atlantic salmon (*Salmo salar*) post-smolts usually swim close to the surface (<3 m), but make irregular dives down to 7 m depth (Thorstad et al. 2012). Adult salmon and adult sea trout (*Salmo trutta*) also occur mainly in the upper 5 m in the water column both when returning to rivers and migrating out again after spawning (Davidsen et al. 2013, Thorstad et al. 2016). Although diving intensity increases with time and distance from the targeted estuary, adult Atlantic salmon show large individual variation in how deep they dive, from >300 m during outward migration and around 100 m during inward migration (Kjellman 2015). The few studies of depth use of both Atlantic salmon and sea trout in their marine migration have been conducted during the summer months, but more knowledge is needed during other times of the year (Thorstad et al. 2016). From the perspective of a migrating salmonid, a suspension bridge using TLP or SFTB, affecting the upper water levels (<20 m) would be preferable to having a pontoon-supported structure.

Little is known about the effects of habitat alteration due to bridge or tunnel designs on marine mammals. The distribution of marine mammals in Norwegian fjords is linked to the distribution of prey, which means that any effects of bridges on prey species might indirectly affect the distribution of marine mammals. Direct effects, such as a barrier effect have not been addressed, but the diving behaviour of species that are common along the Norwegian coast could help identify potential conflict-depths. Harbour porpoises (*Phocoena phocoena*) can dive to more than 400 meters, and foraging depths may be related to the water depth (Nielsen et al. 2018, Westgate et al. 1995). Dives that are related to transiting behaviour are typically V-shaped, rather than U-shaped foraging dives, and occur primarily within the top 20 m (Bjørge 2003). Harbour seals (*Phoca vitulina*) can dive to 500 m, but studies performed in different areas showed conflicting results for average diving depths. One study, performed in the St. Lawrence estuary (Canada) indicated that more than half of the recorded dives occurred within the top 4 meters (Lesage et al. 1999), while a study performed in Norway indicated that seals often dive to the bottom to forage (Bjørge et al. 1995). Depending on the design of the bridge, entanglement may be considered a pressure. Although whale entanglements in underwater cables, such as telecommunication cables, have been reported in the past, such events are considered rare (Wood & Carter 2008). However, cables that may be used in the design or anchoring of floating bridges may differ from telecommunication cables. There are currently no methods to deter marine mammals from the vicinity of cables. Deterrent devices that are used on fishing gear or near construction activities are developed for short-term use only.

Connectivity
Artificial structures may increase connectivity of species by acting as steppingstones. Steppingstones across unfavourable stretches of habitat such as extensive soft sediment areas may aid dispersal of organisms or resources that previously only rarely transgressed a barrier. For hard-bottom organisms, the large areas of ocean or even coastal areas that lack or have low densities of hard substrates can be a natural barrier to dispersal. Artificial structures provide new hard substrate, which may be used by some species in addition to their natural substrates and may provide new dispersal pathways by serving as destinations and sources of larvae. Also, coastal structures may provide habitat for species dispersed by shipping and other vectors. Dispersal of species with short pelagic larval durations may particularly benefit from artificial structures serving as 'stepping stones', while species with longer pelagic larval durations may be less affected (Bishop et al. 2017).

3.2.2 Noise

Sound is one of the key pressures associated with anthropogenic activities in the marine environment. Airborne sounds of certain activities can have a relatively large range (Van Renterghem et al. 2014), and may disturb behaviour of seals or seabirds in some situations (Acevedo-Gutierrez & Cendejas-Zarelli 2011). However, ecological consequences of underwater noise can be far more severe. Since water has a much higher density than air, sound travels much faster and further underwater (Jelle et al. 1988). The perceived intensity of sound is also much higher underwater. Many aquatic organisms rely on sound production, transmission and reception for key aspects of their life-histories. Sound is used for orientation, migration, habitat selection, communication, mating behaviour and the detection of prey or predators (Dolman & Jasny 2015, Kuşku et al. 2018). Anthropogenic sound can therefore influence many species throughout the food web, including fish, marine mammals and plankton (Culloch et al. 2016, Kuşku et al. 2018, McCauley et al. 2017). However, this important source of information is under increasing threat due to the increased prevalence of underwater human-produced sounds. A wide range of human activities produce sound in the hearing and sound production ranges of a wide range of organisms (**Figure 6**). However, since floating and submerged bridges are so cutting edge, little to no information exists on their contribution to sound pollution. Conclusions must therefore be drawn from studies of other sound pollution sources and extrapolation to floating and submerged bridges.

Focus of marine sound pollution literature is currently biased towards marine mammals (Erbe 2012), though the studies that do exist also find anthropogenic sound impacts on fishes, invertebrates, marine birds and reptiles (Gentry 2002, Murchy et al. 2019, Popper & Hawkins 2019, Sørensen et al. 2020). Effects of noise on marine animals range from death to physical injury, displacement, and behavioural changes. Physical injury may come in the form of physical damage to the ear or swimbladder (Smith & Monroe 2016), or physiological changes reflecting, for example, stress (Celi et al. 2016). Masking by anthropogenic noise can cause a decrease in detectability of biologically relevant sounds such as those of predators or prey, sounds of conspecifics or acoustic cues used for orientation (Kaplan et al. 2016, Pine et al. 2016). Behavioural responses are varied and can reflect both startle responses and short- or long-term avoidance of sound sources (Popper & Hawkins 2019). While reactions such as startle response may only be transient, avoidance can result in changes to migration routes or abandonment of feeding or breeding grounds (de Jong et al. 2020). It is the population scale effects resulting from all these effects of anthropogenic noise that guide the assessment of severity. If noise impacts on populations in a way that causes population declines, then regulation and mitigation will need to be more restrictive than if the populations can tolerate the impacts.

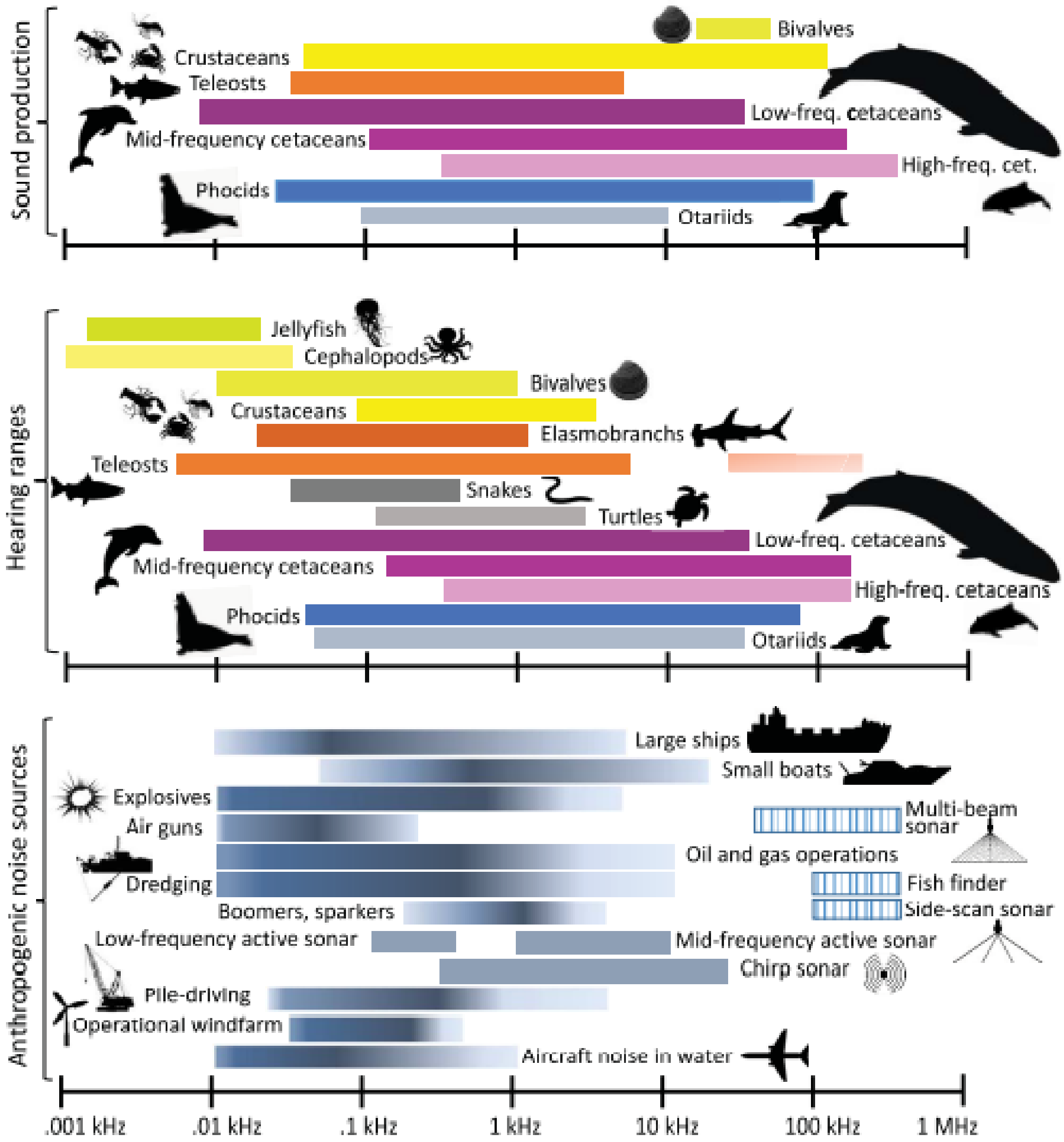

Figure 6. Sources and animal receivers of sound in the ocean soundscape. Approximate sound production and hearing ranges of marine taxa and frequency ranges of selected anthropogenic sound sources. These ranges represent the acoustic energy over the dominant frequency range of the sound source, and colour shading roughly corresponds to the dominant energy band of each source. Dashed lines represent sonars to depict the multifrequency nature of these sounds. Reproduced from Duarte et al. 2021.

Marine mammals

The majority of studies that address the ecological effects of anthropogenic underwater noise are focused on marine mammals (Cominelli et al. 2018, Gervaise et al. 2012, Koschinski et al. 2003, Nabe-Nielsen et al. 2014), which rely heavily on sound for communication, prey location, orientation and predator avoidance (Kastelein et al. 2013). Based on sound production and perception (hearing), marine mammals can be divided into different groups (see also **Figure 6**). Baleen whales (mysticeti) use low-frequency sound for communication, while toothed whales (Odontoceti) primarily rely on high-frequency sound for finding prey (echolocation). Seals (including all seals, sealions and walruses within the families Phocidae, Otariidae & Odobenidae) use a wide frequency range that falls between the two whale groups. All three groups are represented in Norwegian waters, and members of each of these groups can be found near the coast. The most common baleen whale in Norwegian waters is the Minke whale (*Balaenoptera acutorostrata*) (Hammond et al. 2017) but several other species are also frequently observed along the Norwegian coast. While baleen whales can be found in Norwegian fjords, this is more common in northern Norway. However, baleen whales communicate using low-frequency sounds, and are therefore sensitive to low-frequency anthropogenic sounds (Terhune & Killorn 2021), which can travel over long distances. This means that potential consequences of activities that produce low-frequency sounds should be considered, even if the activity is located in the fjords. Some marine mammals are often found in the fjords along the coast of southern Norway. Harbor porpoises are abundant along the entire Norwegian coast and are often found deep in fjords. Like other toothed whales (e.g. dolphins, sperm whales and pilot whales), they use high-frequency sound to locate prey (echolocation) (Carstensen et al. 2006). Two species of seals are also common along the Norwegian coast and are often found deep inside fjords: harbor seals and grey seals (*Halichoerus grypus*) (Olsen et al. 2010, Øigård et al. 2012). Their hearing overlaps with that of both baleen whales and toothed whales, and sound plays an important role, for example in the reproduction process (mating calls) and acoustic detection of predators, such as killer whales (Hastie et al. 2015).

Seabirds
Studies on the effects of underwater sounds on seabirds are lacking. One effect that has recently come to light is the masking of the sounds from seabird's prey. Recent studies into the hearing of great cormorants shows that they have a better sense of hearing in water than they do above the surface (Baker 2020, Mooney et al. 2019). Most seabirds have a poor sense of sight underwater, thus cormorants are more likely to hear the fish they are trying to catch, instead of seeing them before they are close to them. Most seabirds will first locate their prey by smell, following chemical trails like dimethyl sulphide produced by plankton to find areas of high productivity (Baker 2020). Thus, predation by seabirds may be impacted by underwater noise.

Bridges as a source of noise
Anthropogenic sound can be classified into two groups; *impulsive sound* most commonly produced during construction phases, and *continuous sound* most commonly produced during operational phases.

Impulsive noise – construction phase
The construction phase of floating bridges is short-term, however, sound production during this phase can be of higher intensity and therefore warrants consideration. Sound types and intensities will vary with construction type. Sound sources from the construction phase are piling, drilling, groundwork and increased road or boat traffic (Thomsen et al. 2006). Other than traffic sounds, these are typically transient, brief (<1s), broadband and show high peak sound pressure with a rapid rise time and rapid decay and are termed impulsive sounds. Piling is the most commonly studied of these. Passage of sound and vibration into the substrate, which can be caused by sources such as pile driving, may result in waves propagating through the substrate, both as compression waves and interface waves (Popper & Hawkins 2019). They may generate evanescent sound pressure and particle motion waves that propagate through the water. This effect can occur both during underwater piling, but also when piling occurs near to the marine environment, as is the case when building landfall arrangements for bridges.

While few studies exist, those existing studies find both considerable effects of impulsive sounds, but also considerable variation between species and settings (Popper & Hawkins 2019). Physical injury, such as tissue damage or temporary hearing loss may occur when organisms pass a given cumulative level of sound energy (Halvorsen et al. 2012a, Halvorsen et al. 2012b, Smith & Monroe 2016). Behavioural changes such as altered feeding behaviour may also ensue (Roberts & Laidre 2019). In many cases however, those organisms that are able to do so will avoid the affected area during construction works (Popper & Hawkins 2019).

Construction of various bridge designs (floating or traditional) might require pile driving, which can have a devastating effect on many marine mammals (Brandt et al. 2018, Lindeboom et al. 2011). Pile-driving leads to a dramatic reduction in sound production by porpoises, which can either indicate a reduction in foraging and socializing behaviour (best case scenario), or it can indicate that porpoises leave the area altogether (Brandt et al. 2011). This effect is noticeable within 20 km from the construction area, but it is possible that porpoises are affected at distances up to 50 km (Dähne et al. 2013). Area avoidance behaviour in response to pile-driving events have also been recorded in seals, and both seals and porpoises within 10 km of the sound source are exposed to sound levels that are sufficient to cause temporary or long-term hearing damage (Hastie et al. 2015). One possible mitigation measure to reduce the exposure of marine mammals to impulsive (temporary) noise, is the deployment of bubble-net curtains during the construction activity (Wursig et al. 2000; Verfuß, 2014). These bubble-nets create an air barrier which reduce the radiation of noise.

Continuous sound - operational phase
Noise from the operation phase is typically long-duration signals that can increase the overall sound level in the environment for extended periods of time. In the cases of floating or SFTB this will likely arise from transfer of vibrations resulting from traffic over or through the bridge, or it's natural resonance which varies with wind or current. This will be transferred to the water column through the submerged structure, or in the case of submerged tunnels, through the tunnel itself. Activities onshore, including the passage of vehicles, may increase noise levels in the sea, lakes and rivers, especially if they generate substrate vibration. A recent study by Evergreen Point floating bridge across Lake Washington, Abadi et al. (2018) found that noise levels measured in the lake near to the bridge followed public data on both traffic load and wind speed over the bridge. Likewise, another study showed that passing vehicles in a tunnel (within a riverbed), radiated low-frequency (12-25 Hz) at approximately 14 dB greater levels, compared to the background noise (Song et al. 2020). However, while this demonstrates that sound is transferred from the bridge to the surrounding aquatic environment, the spatial extent of the elevated sound levels requires further research.

Though the sound intensity during the operational phase may often be lower than for construction noise, their continuous character can cause long term impacts, particularly through behavioural changes. Anthropogenic sounds may interfere with foraging behaviour either by masking the relevant sounds or by resembling the sounds that the prey may generate (Purser & Radford 2011). Likewise, avoidance behaviour by prey may depend on listening for the sounds that the predators produce, either deliberately or inadvertently (Luczkovich & Keusenkothen 2008, Remage-Healey & Bass 2006). If these impacts are biased to the advantage of either the predator or the prey species, they may cause population scale changes. Another potential impact regards movement and migration. Many fishes and marine mammals migrate between feeding or spawning areas. During migrations, they may use a variety of cues to orientate and navigate, including natural soundscapes. If these are altered by noise at key frequencies, or high intensity, ability to navigate may be reduced and/or altered. High level sounds may also cause direct avoidance responses of a given area (Montgomery et al. 2006, Stanley et al. 2012).

Sound is also used directly in communication between individuals of the same species. Communication during spawning is a common example. Any interference with detection of spawning sounds can have a significant effect on reproductive success of a population (de Jong et al. 2020, Popper & Hawkins 2019).

Mitigation measures that were developed to deter marine mammals or other animals from a certain location, such as fishing nets or pile-driving locations, are all only used during short periods. It is therefore important to consider the continuous noise levels during the design phase of the floating bridge, and to adopt a design that is aimed to minimise the radiation of continuous noise. The soundscape that is produced by a floating bridge in operation should be estimated, in order to evaluate potential effects on local fauna.

Anthropogenic noise generated by today's solutions
Current crossing solutions are by means of conventional bridges, tunnels, and ferries. These solutions can generate sound pollution during both construction and operation phases, and it is therefore important to consider these during evaluation of potential new solutions. Current state-of-the-art bridges (e.g. cable-stayed bridges or suspension bridges) require multiple support towers with bottom mounted fundaments, depending on the total required span. Each contact point with the water and seabed provides a point for transmission of soundwaves and vibrations. In addition, noise generated during the construction phase will increase relative to the number of structures being built. Very few studies exist that quantify sound pollution from bridge structures. However, in a recent study of an international bridge crossing between Norway and Sweden, De Clippele & Risch (2021) found significant differences in sound levels on the nearby Tisler cold-water coral reef pre- and post-border closure due to COVID-19. This demonstrates the existence of noise transfer from bridges to the marine environment, at least at busy bridge crossings.

A significant proportion of anthropogenic noise in the ocean is created by motorised vessels, including large ships, ferries, fishing and pleasure boats (Erbe 2013, Erbe et al. 2012). Indeed, during the initial COVID-19 lockdown, a reduction in shipping traffic was reflected in noise levels in the shipping band of frequencies (Thomson & Barclay 2020). Most vessels produce predominately low frequency sound (i.e., <1 kHz) from onboard machinery and hydrodynamic flow around the hull. Cavitation at propeller blade tips is also a significant source of noise across all frequencies (Ross 1993). Low frequency sounds from ships can travel hundreds of kilometres and can increase ambient noise levels over large areas of the ocean (Ellison et al. 2012). Sound production will be to some extent mitigated by new generation boats with electric boat motors and boat design to reduce sound from, for example, machinery (Parsons et al, 2020).

However, sound production from boats will not be entirely eliminated. It ought to be noted that when considering boat traffic from much of the literature in comparison to applications in Norway, many of the studies have been conducted in busy international ports or with the combination of all boat traffic (e.g. shipping, ferries, fishing and pleasure) in focus. Ferries, which are the focus of the current study, make up only a proportion of the boat generated noise. It is difficult to compare the sound-related impact of a (floating) bridge with ferries in the same place, that transport the same number of vehicles. Both solutions will generate different soundscapes, as bridges produce a relatively continuous sound level, while the sound from ferries is more localized and temporary. To our knowledge, no studies have been performed to compare the sound production of (floating) bridges with that of ferries, and their impact on the local ecosystem.

Sound exposure criteria and guidelines
Sound exposure criteria define the levels of sound that are likely to affect aquatic animals negatively, in order to enable regulation of noise generation in aquatic environments. Principal focus has been placed on marine mammals, with little effort placed on developing criteria and guidelines for fishes or invertebrates (Popper & Hawkins 2019). Underwater noise is included in the European Union's Marine Strategy Framework Directive (EU 2008), with the purpose of maintaining good environmental status in the marine environment. The Swedish Environmental Protection Agency published a review solely focusing on pile driving sounds (Andersson et al. 2016b). In this review they propose maximum exposure values based on interim values proposed by the USA (Buehler et al. 2015). These values have a very limited scientific basis and will be adapted in time, but they at least set a precedent for the use of sound exposure criteria and guidelines and an impression of guidelines that will be implemented in the future.

3.2.3 Light

Light pollution is increasing, and artificial light sources may have great impacts on many animals (see literature review in Follestad 2014). For migrating birds, collisions caused by artificial light pollution are a significant source of mortality. Laboratory studies have demonstrated that birds have different visual sensitivities to different colors of light. In a study of the impact of wavelength on phototaxis at two gathering sites of nocturnally migrating birds in Southwest China, short-wavelength blue light caused the strongest phototactic response (Zhao et al. 2020). In contrast, birds were rarely attracted to long-wavelength red light. The attractive effect of blue light was greatest during nights with fog and headwinds. Zhao et al. (2020) thus suggest that switching to longer wavelength lights is a convenient and economically effective way to reduce bird collisions.

Artificial light sources can, especially under some weather conditions, cause migratory birds to fly toward a light source. Some of these effects are summarized in Follestad (2014). Artificial light sources have increased dramatically in recent decades, with 23 % of the world’s land surface between 75°N and 60°S experiencing light-polluted nights (Falchi et al. 2016). This has seriously affected bird migration (La Sorte et al. 2017, Cabrera-Cruz et al. 2018, Horton et al. 2019) and their choices of stopover habitat (McLaren et al. 2018). Migratory birds may aggregate around light sources (Van Doren et al. 2017), and they may thus collide with lighthouses, ships, oil rigs, airports, communication towers, and tall buildings that are illuminated at night (Avery & Cassel 1976, Crawford & Engstrom 2001, Jones & Francis 2003, Gehring 2009, Kerlinger 2010, Merkel & Johansen 2011, Longcore et al. 2008).

A number of factors influence how birds respond to artificial light, including the time of year, weather conditions and properties of the light (Zhao et al. 2014). Poot et al. (2008) found that red light tends to attract migratory birds and suggested that the failure of geomagnetic orientation abilities under red light stimulation may cause collisions with artificial light sources. However, the notion that red light attracts birds has been questioned (Evans 2010). With the current advances in development of new lamps, such as LEDs, and studies on effects of different wavelengths and temperature of the light, an update on this should be made before deciding lightening of components of floating bridges. Design of lights on deck (as illustrated in **Figure 7**) may help reducing the amount of light spread to the surroundings.

Figure 7. The suspension bridge crossing Bjørnarfjord, where lights on deck do not spread light to the surrounding sea surface (from Statens Vegvesen).

3.2.4 Gateways

Bridges and tunnels may introduce mammalian predators to new sites/islands. All types of floating bridges may act as a spreading route for carnivores (such as red fox *Vulpes vulpes*, European badger *Meles meles*, European pine marten *Martes martes*) from the mainland to islands where they are currently not present. This may increase predation on many birds, mammals, amphibians etc. on these islands that are not adapted to such predation. Bergan & Giæver (2002) describe environmental consequences from Nordøyvegen based on the prerequisite that these predators will NOT spread to the island connected by a number of bridges and tunnels as barriers to stop them, are effective. The American mink *Neogale viso*n is already present along most of the Norwegian coast, and there is little reason to believe that floating bridges may expand its distribution.

If barriers built to prevent spread of mammalian predators are not 100 % effective, introduction of new predators may have severe effects on populations of birds, wildlife and other animals (like amphibians). When islands become connected to the mainland by tunnels or bridges, there is a real threat that animals on the mainland, or a nearby island, may spread to new islands. This has been well documented on the island Tautra in the Trondheimsfjord, where red foxes, badgers and pine martins crossed Svaet from the mainland to Tautra by the stone causeway (Thingstad 1994). Thingstad (1994) summarized what happened (sitat): *Tautra, including Svaet, was established as a Ramsar area in July 1985, thus earning international status as an important wetland area for birds. However, after Tautra was connected to the mainland via an approximately 2,5 km long stone causeway across Svaet in 1976 it has become inhabited by predators (particularly foxes and pine martens) that were previously not present there. This has led to heavy predation pressure on the seabird colonies on the island which, among other things, has strongly decimated the nesting populations of eider ducks and common gulls.*

To mitigate the spread of predators, barriers must be planned from the beginning and must be specific for the local needs. A replacement of a stone causeway by a bridge and physical barriers, as a mitigating measure, may have a positive effect of the wildlife.

3.2.5 Other

Effects of road fills
Where floating bridges may include road fills or stone causeways at one or both ends of the link, several effects need to be discussed. In an environmental impact assessment of a planned approximately 1.5 km road link including a 400 m bridge from the island of Kråkvåg to the neighboring island of Storfosna across Kråkvågsvaet, Thingstad & Hokstad (1997) discuss the very local effects of changed currents close to a small road fill in one end of the road. The shallows and rocky/muddy shores at Kråkvågsvaet have achieved international conservation status as a Ramsar area because of their great ornithological qualities as a wetland. Marine biological investigations have shown a demersal fauna rich in species and individuals associated with the shallows and its currents. One alternative for the bridge, if chosen, would cause serious changes to the pattern of currents. This could give a significant reduction in the production of several groups of demersal marine organisms especially important as a source of food for several aquatic bird species.

A road fill can also be a new site for breeding otters or minks, if there is a lack of safe breeding sites nearby. Increase in otter numbers could be considered as positive as it may give locals better opportunities to experience this native species. The mink may, however, be a negative supplement to the local biodiversity, as a ferocious predator of several species. Otters may displace mink close to its dens, with a possible effect of reducing the predation pressure by the mink (Follestad et al. 2005).

Floating or submerged bridges may have an advantage over bridges with towers and wires, which might cause collisions with migrating birds. This may be the case both for seabirds during foraging and during ordinary seasonal migrations.

When bridges cross deep fjords, there will probably be small or no conflicts with feeding areas for seabirds. But in areas near to known, or suspected, important feeding areas, mapping how seabirds utilize the area close to the bridge should be performed in an early stage of the planning phase. This should also include alternative crossing alternatives like “normal” bridges or ferries.
Bridges as nesting place for birds

Birds may use bridges for resting or nesting, and their acid droppings may badly damage concrete. For floating bridges, kittiwakes may start breeding on edges under the bridge, as they have done at the Gjermundnessund bridge. Some years ago, nests were washed away to prevent such damage, but now a foil has been added on the concrete in order to prevent damage and enable the nests stay (A. Follestad own information). Problems with kittiwakes breeding on oil platforms have been discussed by Christensen-Dalsgaard et al. (2020). If kittiwakes and other birds could potentially start breeding on a floating bridge, concern should be taken to minimize problems (see also Bird Control under Bridges).

3.3 Ecological effects of ferries

A ferry crossing is a less permanent alternative to bridges or tunnels. Ferries do not form a constant ecological pressure, but each crossing can be linked to multiple environmental impacts. Although few studies have addressed the effects of ferries in isolation, many effects related to shipping also apply to ferries. A comprehensive overview of ecological effects related to coastal shipping is presented in Jägerbrand et al. (2019).

Birds
Most studies investigating the effects of ship traffic on seabirds in offshore waters have focused on behavioral responses of scavenging seabird species towards fishing vessels (Votier et al., 2010; Tew Kai et al., 2013; Bodey et al., 2014; Sommerfeld et al., 2016; Le Bot et al., 2018, see references in Burger et al. 2019). With respect to bird disturbance by ships, only few studies exist, mainly due to the difficulty of studying these interactions. Using research vessels as observation platforms, high response distances from approaching vessels were recorded for common scoters (*Melanitta nigra*) and divers (Bellebaum et al., 2006; Schwemmer et al., 2011; Fliessbach et al., 2019). A recent study by Mendel et al. (2019) found the strongest impact of ships on red-throated divers (*Gavia stellata*)for a radius of 5 km and within 5 min of the passage of a ship. However, long-term effects over several hours could not be investigated.

Literature on environmental effects of ferries on seabirds is primarily focussed on high-speed passenger ferries crossing open sea like in the North Sea, Skagerrak, Kattegat or in the Baltic Sea, with partly shallow waters. We have found no studies on disturbance effects on birds from the typical slower Norwegian ferries.

Noise
Vessel noise is perhaps the most prominent pressure associated with ferries, and with shipping in general (Jägerbrand et al. 2019; Cox et al, 2018). Sound levels are related to gross tonnage, where small or medium size vessels (such as ferries) typically produce sound levels up to 175 dB re 1 μPa (Kuşku et al. 2018). A car ferry line across the Saguenay Fjord (Canada) added 30-35 dB to ambient noise levels during crossings, which was substantially higher than the noise contribution of smaller whale watching vessels in the same area (Gervaise et al. 2012). Main sources of shipping noise include engines and other machinery, water displacement from the hull and propellor cavitation. The most intensive shipping noise occurs within 10 to 1000 Hz (Celi et al. 2016, Jagerbrand et al. 2019), although smaller vessels may produce intense high-frequency noise as well (**see Figure 6**). Shipping noise may lead to area avoidance behaviour (Fliessbach et al. 2019), masked communication (Terhune & Killorn 2021), elevated stress (Kuşku et al. 2018) and behaviour disturbance (Dehnhard et al. 2019). However, due to the intermittent character of ferry-induced noise, the long-term impacts of sound pollution from ferries may be less severe, compared to continuous sound sources of similar intensity and frequency ranges (Blom et al. 2019).

Other impacts from ferries
Collisions between moving vessels and marine organisms have been reported throughout the world, particularly when large whales are involved. However, collisions with other marine mammals, birds and fish also occur, although it is difficult to evaluate the potential risk of collisions, due to a lack of data (Schoeman et al. 2020). In addition, shipping may contribute to a number

of other environmental pressures, including pollution, either in air or in water (Andersson et al. 2016a, Corbett & Farrell 2002), marine litter (Grøsvik et al. 2018), and light pollution (Jägerbrand et al. 2019).

Electric ferries

The installation of electric engines in ferries may help reduce certain ecological pressures, such as pollution and noise. The radiated noise from a vessel is comprised of various elements, including cavitation noise of the rotating propellor, sound from machinery, which is transported through the vessel hull, and the sound of water displacement by the vessel. The use of electric engines in vessels should not affect cavitation noise or sounds from water displacement, but it is likely to reduce the sound of the engine itself. As a result, electric engines should reduce the overall radiated noise level of vessels. Although reports comparing the ecological impact of conventional ferries and electric ferries are scarce, one publication found a significant reduction in noise, as a conventional ferry was 12 dB louder at distance of 55 m than an electric ferry. Low frequencies (<500 Hz) were specifically reduced, up to 25 dB at short distances from the source (Parsons et al. 2020).

4 Expert evaluation

The literature review has gathered the knowledge basis currently available for assessing potential effects of floating bridges on the environment. In this section the authors process the available information to provide expert evaluation of the potential positive or negative effects of floating bridges. This list is not exhaustive and can be refined and improved as more information becomes available. Potential mitigation measures are suggested in chapter 5 of this report.

It is important to highlight that the effects listed in the sections below are not independent and may result in cumulative effects on animal populations and the environment through combination with other impacts (e.g. light, physical barriers or other noise effects).

Expert evaluation of potential impacts from anthropogenic noise from floating or SFTB bridges

The following potential impacts of noise from construction of floating or SFTB bridges have been identified:

- *Habitat quality reduction as a result of avoidance* - anthropogenic noise may cause marine animals to avoid areas in the vicinity of the construction site. This is relevant for marine invertebrates (zooplankton, bottom fauna), fish and mammals. The extent of the impact will depend on the spatial extent of the area avoided and eventual periodicity. Assuming the construction phase is not long lasting, this will likely not result in population scale effects. However, if construction takes place during important feeding or reproduction periods it may result in population scale effects. Therefore, such periods must be identified prior to the construction, and construction phases that have consistent noise effects should be avoided during these events.
- *Physical injury* – anthropogenic noise may cause physical injury or death to those animals unable to avoid it. This is relevant for marine invertebrates (zooplankton, bottom fauna), fish and mammals. The extent of the impact will depend on the spatial extent of the area in which physical injuries occur and the duration of the impact. If the extent is widespread, then population scale effects may occur. Construction phases that are likely to produce high levels of noise (e.g. pile driving) require mitigation measures that are specifically tailored for the local fauna should be investigated. Potential mitigation measures are suggested in chapter 5 of this report.

The following potential impacts of noise from operation of floating or SFTB bridges have been identified:

- *Migration barrier* – anthropogenic noise may create a barrier to movement through, or into, an area. This is particularly relevant for salmonid migration in and out of freshwater and migrations of marine fish and mammal species between different habitats. The extent of the impact will be dependent on frequency range, intensity and periodicity. Variability in sound intensity or presence with, for example, traffic or weather conditions (wind), will drive the degree of influence.
- *Habitat quality reduction as a result of masking* – anthropogenic noise may mask signals marine animals use for activities such as foraging, predator avoidance and reproduction. This is relevant for marine invertebrates (zooplankton, bottom fauna), fish and mammals. The extent of the impact will depend on sensitivity of each species to the frequencies produced, sound intensity and periodicity (i.e. whether sound pollution is present at high intensities during key feeding or reproduction seasons for each species)
- *Habitat quality reduction as a result of avoidance* – anthropogenic noise may cause marine animals to avoid areas in the vicinity of the bridge structure. This is relevant for marine invertebrates (zooplankton, bottom fauna), fish and mammals. The extent of the impact will depend on the spatial extent of the area avoided and eventual periodicity.

Knowledge about local biodiversity, migratory species and migration routes is essential to optimize the structure design to minimize environmental effects.

Expert evaluation on the comparison of anthropogenic noise from floating or SFTB bridges

It has been documented during the literature review and expert evaluation that all methods of waterway crossing can result in elevated levels of anthropogenic noise in the surrounding marine environment. The effect of noise at a given location is dependent on many things. The geological structure of the surrounding (underwater) area, the species that are present in, or migrate to or through, that area and which ecosystem functions it provides. Therefore, environmental impact assessment is needed on a case-by-case basis to identify problems, needs and solutions prior to the bridge planning phase. There are, however, some general conclusions that can be drawn:

- *Floating bridges* have less contact structures with the seabed. This is anticipated to reduce the scale of some construction-based noise, such as that from piling. It may also reduce the potential for transfer of noise during the operation phase through contact with the seabed. However, it is currently unknown whether there is any difference (positive or negative) in transfer of sound through fixed contacts with the seabed or floating structures. Further investigations is therefore required to document the full advantages or disadvantages of each approach.
- *Boat traffic* has been documented in the literature review as being a source of underwater noise. The majority of studies included all boat traffic, not only ferries. Therefore, it is the expert opinion that in most cases, reduction of ferry traffic through replacement with a bridge will not cause major reductions in boat-related underwater noise. Likewise, although ferry traffic will likely increase over time (for example resulting from increased traffic on the better connected E39), it is anticipated that an increase in new, modern ferries will not result in noise increases to significant levels. This must, however, be considered case by case taking into account site-specific conditions and information.

SFTBs are a novel approach which are largely untested. Testing is required to investigate the sound transfer properties of SFTBs to the surrounding aquatic environment. Questions that need to be answered include: To what extent does sound from the SFTB structures transfer to the aquatic environment? Is sound from traffic vibrations transferred to the aquatic environment? Do vibrations or movement of the SFTB in the water column cause sound that is transferred to the aquatic environment? What are the common frequencies and sound intensity of the sounds produced? To what extent can this be mitigated through material choice or design? Studying the existing floating bridges in Norway and existing ferry-connection would make it possible to answer these questions.

Expert evaluation on the comparison of effects on the benthic community from floating or SFTB bridges

The following potential impacts from construction on marine benthic organisms have been identified:

- *Destruction of habitat* – during construction of bridge types using anchoring, the sea floor will unavoidably be affected by their attachment and existing habitat will be destroyed.
- *Turbidity in the water column* – installation of anchor systems will result in sediment particles in the water mass. This may affect benthic organisms such as filter feeders and the increased turbidity provides difficulties for visual predators. Depending on length and timing of this phase, it may influence larval production and spreading.
- *Migration barrier* – depending on length and timing of this phase, the activity may impede both inwards and outwards migration of salmonid fishes, resulting in increased mortality.

The following potential impacts from operation on marine benthic organisms have been identified:

- *Habitat quality reduction* – altered hydrodynamics can change sediment distribution, temperature and salinity which may locally reduce species diversity and change species composition.
- *Providing new habitat* – providing hard substrates as new habitats may have both positive and negative implications. On the positive side it may construct an artificial reef that provide shelter and food for many species, thereby increasing biodiversity and biological biomass. On the negative side the population on the structure differs from natural habitats due to its physical properties, it may act as steppingstones for both invasive and native species and act as a bio-filter, depleting primary organic matter in the near vicinity.
- *Physical barrier* – creating a physical barrier in the ocean will affect the hydrodynamics on this water system on many levels as well as migrating species as well as introduce shading.

Knowledge about site specific biodiversity, oceanography and hydrology is essential to optimize the structure design to minimize environmental effects.

Expert evaluation on the comparison of benthic community changes between floating or SFTB bridges

It has been documented in this review that means of crossing a waterway will have effects on the benthic communities. The degree of the effects will vary depending on a range of factors that has to be assessed for each potential development site. But some general conclusions can be drawn:

- A submerged structure will likely have the most profound effect on the benthic communities. A large, submerged structure will have a significant impact on the hydrodynamics of the area. It will also act as a physical barrier for marine animals on both local and regional scale. It will also provide a prominent area of hard substrate for colonisation of a range of organisms, which, depending on the design, may have both negative and positive effects. If supported by pontoons, it will not have any contact with the sea floor which avoids the destruction of habitat in the construction phase, which is positive, but the pontoons also add to the area of new substrate. If supported by anchors, the benefit of avoiding bottom destruction is lost but the surface area is reduced.
- A suspended bridge is likely the solution that will impact the benthic communities the least. Even if supported by anchors and pontoons, the effect on hydrodynamics is minimized and the introduction of new substrate will be considerably less. It will also have a considerably less effect on migratory species.
- To understand the potential effects a construction may have and to best validate mitigating procedures it is very important to have as much local and site-specific knowledge as possible.

Expert evaluation of potential impacts from light from floating or SFTB bridges

It has been documented in the literature that artificial light may affect several plant and animal species (see literature review in Follestad 2014). The effect of floating bridge lighting at a given location will depend on several factors, such as type of bridge, type of light source (lamps) and how they are designed and placed on the bridge. Lamps along the deck are used to secure a safe crossing by cars, bicycles or people, and in towers to warn ships and airplanes. Therefore, environmental impact assessment is needed on a case-by-case basis to identify problems, needs and solutions prior to the bridge planning phase. Some general conclusions can, however, be drawn:

- Lights may, under certain weather conditions, attract birds to circle around them, increasing the risk for collisions with structures of the bridge, becoming exhausted (if they continue to circle into dawn) or the risk of predation.
- Lamps may spread light to the sea surface if they do not have screens to prevent light spreading to the surroundings. This may affect migrating fishes, such as salmon smolt, or attract plankton or small fish to the surface.
- A long row of lamps may be a barrier to migration in an area where no lights have been present before the new bridge.
- It's important to obtain knowledge of the species of concern to understand the extent of the eventual interference, as animals differ in their sensitivity to different colours.

Expert evaluation of potential impacts from gateways from floating or SFTB bridges

The literature review has documented that where floating bridges replace ferries between islands and mainland, they may act as gateways for mammalian predators. If introduced to pristine areas, these predators can become a catastrophe for birds and other animals already present and not adapted to the presence of such predators. Dependent on which species are introduced in this way, ground breeding birds will be most affected in case of foxes and badgers, and birds breeding in trees in the case of pine martens. The risk for bridges acting as gateways will depend on:

- Effects of gates to prevent predators to get access to decks
- Time of the year when they cross the fjord
- Effects of take-out programs to remove predators

It is important that the necessary gates/barriers are planned during the design phase of the project to ensure their 100 % effective function.

5 Recommendations

A number of mitigating measures can be put in place to reduce negative effects of the construction process or during operations or provide positive solutions for wildlife. A number of these are listed below.

In addition, better understanding of the potential impacts of floating bridges and SFTBs through further research will open the door for new mitigation measures.

5.1 Potential mitigation measures that may be built into bridge design

1. Conduct full environmental impact assessments prior to planning, during construction and during operation phases of all structures. That includes (i) evaluation of the area, important features in geology (structures that may affect sound transfer) and biology (species presence, special ecosystem functions such as feeding or reproduction) that may affect selection and design of crossing solution, (ii) baseline study to characterise environmental features, species communities and ecosystem function and to plan the monitoring program, (iii) monitoring during the construction phase, (iv) monitoring during the operation phase.
2. Assess if the scoping part of the environmental impact assessment should be conducted as a participatory dialogue process which will give ownership to the stakeholder and reduce the level of conflicts.
3. Prevent SFTBs and bridges acting as gateways for predators into pristine areas by ensuring that wildlife exclusion measures are 100 % effective in preventing predators like foxes, badgers and pine martens.
4. Adapt lighting on bridges and pontoons to minimize impact. Use lamps with recommended design, colour spectra and temperature, based on the state-of-the-art knowledge available for species in focus.
5. Establish lighting regimes to turn off light in weather conditions that might increase collision risk of wildlife with different bridge.
6. Adapt pontoons for use by breeding birds. Secure pontoon edges (with a low fence?) so chicks do not fall into the sea (they will not be able to climb onto the pontoons). Build small structures on the pontoons to provide shelter for chicks from avian predators.
7. If birds start breeding on green pontoons, lights to warn ships should not shed light into the pontoon to reduce the risk of predation on the chicks.
8. Encircle piling activities with a bubble curtain or other noise reduction techniques to reduce sound transferred to the marine environment (Wursig et al. 2000; Verfuß, 2014).
9. Create submerged bridges in such a way that vibration from traffic movement (or movement of the structure in water?) is limited. Either by insulation or choice of construction material/method.
10. Given enough site-specific information the sound transfer properties of each potential crossing solution could be assessed for the area. For example, in areas with a lot of wind, SFTBs may be better adapted since over-water structures will move more in the wind and transfer more noise to the aquatic environment. On the other hand, areas with strong currents may cause a SFTB to create more noise.
11. Adapt the resonance frequency of a bridge to avoid key frequencies. This however, requires prior knowledge of which species are present and their key frequency sensitivities.
12. Seed structures with indigenous species, such as vegetation or invertebrates. These can occupy space that could otherwise be rapidly colonised by opportunistic non-native species and help to preserve native biodiversity.

13. Use environmentally friendly materials in structures to improve performance and durability, as well as reduce ecological stress and encourage the development of natural communities.
14. Bioprotection of the structure can also reduce the maintenance costs due to increased lifespan. Reducing the magnitude and frequency of structural maintenance improve ecological stability (reduced anthropogenic intervention), as well as reduce maintenance costs.
15. Incorporate microhabitats into artificial structures to promote diversity of species and provide refugia from both abiotic and biotic stress.
16. Integrate ecological considerations into the design of repair and maintenance of marine infrastructures during the lifetime of the structure.
17. Consider the ecological value of areas prior to planning bridge type and placement. These will be identified during the environmental impact assessment area evaluation phase.
18. Avoid construction on key areas of conservation value. Areas considered essential habitat for threatened or endangered species should be excluded from development plans.

5.2 Research areas on the environmental impacts and mitigation measures of floating bridges

Anthropogenic noise

- More research is needed into noise originating from floating bridge constructions and its impact on key species. For example, documenting the characteristics of sound (e.g. frequency range and peak frequencies) produced by bridge constructions and mapping (modeling) the distribution of noise within the affected marine area. While this ought to be conducted for each bridge construction, general research on typical fjord crossings will also provide valuable knowledge.
- Noise thresholds causing avoidance and physical injury for key species ought to be obtained from literature, or where necessary, experimentation.
- Combining mapping of distribution of bridge related noise and information on noise thresholds of key species will enable mapping of zones of impact for given species. This will enable conclusions to be drawn on whether the floating bridge construction causes physical injury (particularly during the construction process), habitat quality reduction as a result of avoidance, habitat quality as a result of masking of communication, or is a migration barrier preventing passage between two areas.
- In order to consider potential impacts relative to alternative crossing solutions such as traditional or electric ferries, studies on the character (e.g. frequencies) and extent of noise originating from these alternatives ought also to be conducted.

Light

- More research is needed on how birds will be attracted to light on bridges in weather conditions when they are known to gather around light sources like lighthouses, oil platforms or marker lights on high structures. This may cause collisions with structures, exhaustion after circling around them for a long time, or increased predation if they keep flying into sunrise (when they become more visible for predators). Knowledge on flight patterns or migration routes when crossing large bridges may help design mitigation measures, as rules for turning off light in short periods to let birds escape from the light. At the local level, knowledge of the local species is important to understand the extent of possible interference.

Habitat changes

- It is very important to gain more information on nature inclusive design/ecological engineering of the bridges, taking material composition, texture and macro-design into consideration. Optimizing these areas will strongly influence the benthic communities attaching to a floating bridge and its possible function as an artificial reef or as stepping stone for opportunistic or non-native species.
- To understand how floating bridges may function as migration barriers more research is needed on how migrating marine species (mainly mammals and fish) use the water column in this phase. Here should also the hydrodynamic changes caused by the bridge be included.
- Study how natural communities on the structures, or bio-protection, may increase durability and ecological stability and reduce maintenance cost.

Gateways

- One prerequisite for building new bridges and tunnels should be 100 % effective ports or barriers to prevent mammalian predators to get access to areas/islands where they are not present today. More research is needed on how predators behave when they meet such barriers, as well as their effectiveness by e.g. camera surveillance (infrared cameras or by developing methods for recognition by using artificial intelligence?). This could be done by using existing barriers, like those being built on the new Nordøyvegen.

Other

- More research is needed to see how birds will respond to (green) pontons on submerged floating twin-tube bridges (SFTB) as potential breeding sites for some species, and how they should be designed (avoid chicks falling off them when running to seek shelter, but still make maintenance work possible).

Mitigation

- A consideration of the environmental aspects needs to be a part of the very early stages of a bridge construction.
- Environmental impact assessment – design a standard protocol on what needs to be investigated and how it needs to be carried out.
- Research on best design/way to carry out mitigation. E.g.
    - Best lighting regimes - how design of poles and lamps and choice of colour etc. can mitigate some effects (see section 4).
    - Best way to prevent SFTBs and bridges acting as gateways - we need to test their effectiveness and, if they can't be expected to be 100 %, establish routines for taking out predators immediately when passing of these barriers by a predator is observed.
    - Research into construction design to minimize vibration and noise generation.
    - Research existing measures to reduce the effects of the construction phase, e.g. bubble net curtains to reduce the radiation of noise produced during pile driving.
- Research into how to design structures to support native benthic communities that do not harm structures e.g. best material for native benthic community growth and how best to seed with indigenous species.

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7 Appendix: Included papers from WoS literature search

Our literature search in Web of Science on October 26th 2021 yielded 1441 articles, and all articles were screened. A systematic literature search tends to have a wide scope, and will always return a large number of irrelevant hits. The following 195 papers were considered relevant for our project:

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