U.S. Offshore Wind Energy Noise Reduction Associated With Installation of Fixed-Bottom Foundations: Workshop Report

May 2023

Rebecca Green[1]
Hayley Farr[2]
Kendra Ryan[1]
Genevra Harker-Klimes[3]
Joseph Haxel[2]
Michael Richlen[2]

[1]*National Renewable Energy Laboratory (NREL)*

NREL is operated by the Alliance for Sustainable Energy, LLC for the U.S. Department of Energy under contract DE-AC46-08GO28308.

[2]*Pacific Northwest National Laboratory (PNNL)*

PNNL is operated by Battelle for the U.S. Department of Energy under contract DE-AC05-76RL0183.

[3]*U.S. Department of Energy (DOE) Contractor*

Prepared for the U.S. Department of Energy Wind Energy Technologies Office. The information presented in this document is considered business sensitive and should not be shared beyond those invited to review by the U.S. Department of Energy.

DISCLAIMER

This work was authored by the National Renewable Energy Laboratory and Pacific Northwest National Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308 and DE-AC46-08GO28308, respectively. Funding was provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the report do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Executive Summary

As offshore wind energy development grows in the United States, solutions are needed to reduce the underwater noise and substrate vibration generated during fixed-bottom turbine installation to help protect marine life. Monopiles are currently the main turbine foundation type installed globally and use impact hammers to drive these large piles as the primary installation method. This installation method is a major source of noise and vibration during wind farm construction. Opportunities exist to reduce the amount of noise and vibration produced during future offshore wind farm development. The use of alternative foundation types and installation methods, as well as innovative noise abatement technologies, would help reduce the potential detrimental effects on sensitive marine species. In addition to noise reduction, there are multiple other reasons to investigate alternative foundation types, including related to soil condition suitability, domestic content and U.S. jobs, and cost implications.

To explore these opportunities, the U.S. Department of Energy's Wind Energy Technologies Office, in collaboration with the Bureau of Ocean Energy Management and the National Oceanic and Atmospheric Administration, funded the National Renewable Energy Laboratory and the Pacific Northwest National Laboratory to organize, host, and facilitate a virtual workshop in December 2022. The goal of the workshop was to gather input from the offshore wind energy community on noise reduction strategies for the installation of fixed-bottom offshore wind turbines in U.S. waters across multiple regions, including the Atlantic Coast, Gulf of Mexico, and Great Lakes, to inform recommendations on future research. The joint lab team convened industry representatives, subject matter experts, and regulators to discuss potential pathways to reduce noise and vibration associated with fixed-bottom turbine installation. Workshop participants also discussed the practicality of using alternative foundations and installation methods, the effectiveness of noise abatement technologies, and research and monitoring needs.

In preparation for the workshop, the team invited experts to be part of a steering committee and worked with its members to help focus activities to meet the workshop goals. Additional pre-workshop activities included developing the invitee list and workshop agenda, reviewing existing construction and operation plans for proposed offshore wind projects, distributing a brief questionnaire to industry representatives, and drafting the workshop discussion questions and Mural boards.

In total, 128 workshop participants provided over 600 comments in response to the 17 group discussion questions used over two workshop sessions. In addition to research topic needs, overarching recommendations across themes included future investments to provide data sharing, consistency, and transparency, and opportunities for sharing the best available science, knowledge, and expertise. The joint lab team synthesized the comments and identified four key research and development themes that could help advance the successful implementation of noise and vibration reduction strategies in U.S. waters:

- Evaluate the **efficacy and costs** of existing piling approaches and available noise abatement technologies, as well as the efficacy and costs of alternative foundation types, innovative piling approaches, and novel noise abatement technologies, including assessing technical feasibility at scale of new technologies and collecting data on underwater sound signature characterization.
- Develop the U.S. **supply chain** to increase access to and availability of noise abatement and monitoring technologies as well as increase production capacity for alternative

foundations (with consideration of differential CO_2 footprints of materials and installation methodologies) and increase use of alternative foundations through investments in ports and installation vessels.

- Address the need to develop **standards** to help provide consistency across models and approaches for alternative foundations, quieting technologies, and monitoring across several topics, including determining design standards, investing in testing construction standards for low-CO_2-emitting materials (e.g., concrete options), and improving and developing sound propagation models.
- Understand potential impacts on **wildlife** from piling noise (impact and vibratory), including acoustic sound pressure for marine mammals, waterborne acoustic particle motion for fishes, and substrate-borne vibration for seafloor boundary fishes and invertebrates; understand the potential cumulative effects from installation of alternative foundation types for multiple turbines and wind farm clusters.

This report provides an overview of the workshop goals and scope, reviews the pre-workshop activities, presents brief summaries of participant feedback, and concludes with detailed research themes and recommendations for future investments. The appendices include the results of the pre-workshop industry questionnaire, the full workshop agenda (including workshop discussion questions), and synthesis of relevant information from the construction and operation plans (e.g., foundation types, installation techniques, and noise abatement systems).

Overall, there was a high level of interest and engagement in the workshop. The sessions provided an opportunity for significant exchange of information between workshop participants from across sectors. Participants identified a variety of opportunities for next steps toward the noise reduction of offshore wind turbine installation in U.S. waters, including recommendations for future investments to provide certainty in the use of new technologies associated with alternative foundation types, noise abatement systems, and efficacy monitoring.

Contents

Abbreviations and Acronyms

BBC	big bubble curtain
BOEM	Bureau of Ocean Energy Management
COP	construction and operations plan
DOE	U.S. Department of Energy
DBBC	double big bubble curtain
GBF	gravity-based foundation
GW	gigawatts
HSD	hydro sound damper
itap	Institut für Technische und Angewandte Physik GmbH
LEEDCo	Lake Erie Energy Development Corporation
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PTS	permanent threshold shift
TTS	temporary threshold shift
WETO	Wind Energy Technologies Office

1.0 Overview

In March 2021, the U.S. Departments of Interior, Energy (DOE), Commerce, and Transportation announced a shared goal to deploy 30 gigawatts (GW) of offshore wind energy in the United States by 2030, while protecting biodiversity and promoting ocean co-use (The White House 2021). From an environmental perspective, marine acoustics issues are a topic of national and international significance, and offshore wind energy development could contribute to increases in anthropogenic noise. Monopiles are currently the main foundation type, representing 64.4% of global installations (Musial et al. 2022), and impact pile driving can be a major source of noise and vibration during wind farm construction that could have serious effects on marine life. In addition to noise reduction, there are multiple other reasons to investigate alternative foundation types – for example, industry may need these to avoid unsuitable soils, to increase domestic content and U.S. jobs, and to provide technical diversity and competition to help lower costs (e.g., Fried et al. 2022).

There are opportunities to reduce noise and vibration during future offshore wind farm development using alternative foundation types and installation methods and innovative noise abatement technologies. Some approaches are already widely used in European wind farm development. Additional approaches are also commercially available, and further achievements in noise abatement may be possible through research and development. To explore these opportunities, DOE's Wind Energy Technologies Office (WETO), in collaboration with the Bureau of Ocean Energy Management (BOEM) and the National Oceanic and Atmospheric Administration (NOAA), funded the National Renewable Energy Laboratory (NREL) and the Pacific Northwest National Laboratory (PNNL) (the "team") to plan a virtual workshop to gather feedback on noise reduction strategies for the installation of fixed-bottom offshore wind turbines to minimize the environmental effects of U.S. offshore wind development.

2.0 Workshop Goals

The goal of the workshop was to gather input from the offshore wind energy community on noise reduction strategies for the installation of offshore wind turbines in U.S. waters across multiple regions, including the Atlantic Coast, Gulf of Mexico, and Great Lakes. NREL and PNNL gathered industry representatives, subject matter experts, and regulators to discuss potential pathways to reduce noise associated with fixed-bottom turbine installation (Figure 1). Participants also discussed the practicality of using alternative foundations and installation methods, the effectiveness of existing noise abatement technologies, and research and monitoring needs.

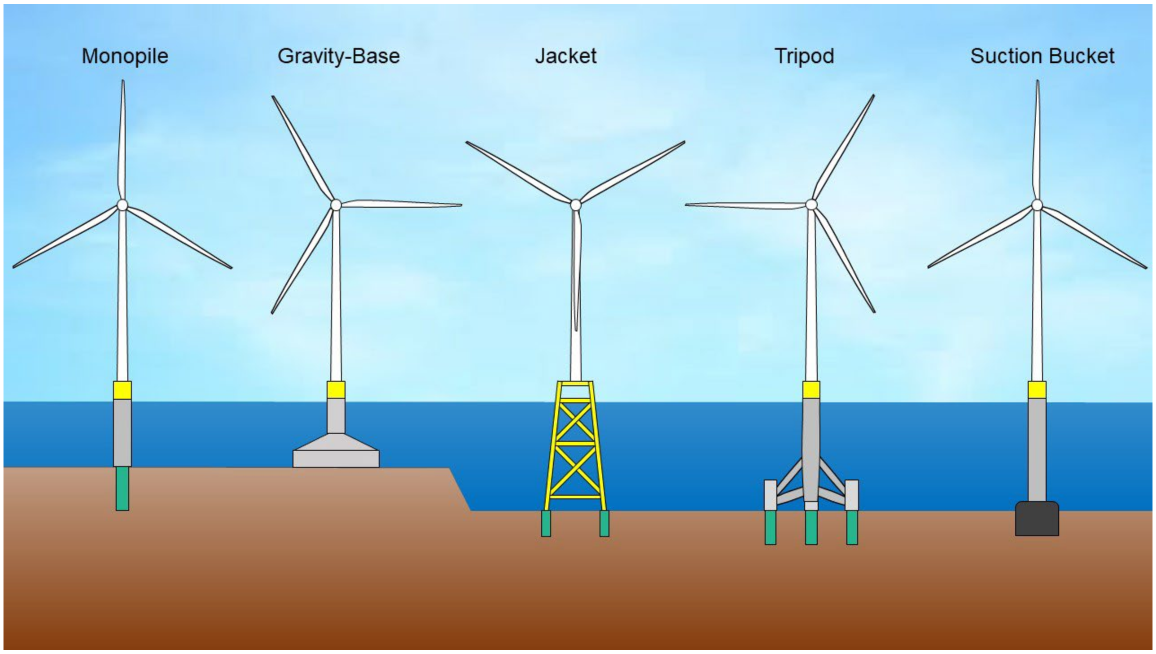


Figure 1. Offshore wind turbine fixed-bottom foundation types. *Illustration by Stein Housner, NREL*

The workshop did not cover noise and vibration reduction associated with support vessels, geological and geophysical surveys, or cable laying, or noise related to other phases of offshore wind energy development (e.g., site characterization, operational noise, decommissioning). With regard to the Federal Advisory Committee Act, the team did not seek to achieve consensus during workshop activities, but instead aimed to gather individual perspectives from industry professionals and subject matter experts. Additionally, it is important to note that the feedback provided by participants was based on personal opinions and could be biased.

3.0 Pre-Workshop Activities

In preparation for the workshop, the team invited experts to be part of a steering committee and worked with them to focus activities to meet workshop goals. Additional pre-workshop activities included developing the invitee list and workshop agenda, reviewing existing construction and operation plans (COPs) submitted to BOEM, distributing a brief questionnaire to industry participants, and setting up the workshop Mural boards.

3.1 Steering Committee

The steering committee was formed to assist with and provide feedback on workshop planning. Committee members included Naomi Lewandowski (DOE), Genevra Harker-Klimes (DOE Contractor), Jill Lewandowski (BOEM), Sam Denes (BOEM), Amy Scholik-Schlomer (NOAA), Zach Finucane (Ørsted), Michael Jasny (Natural Resources Defense Council), and Ruth Perry (Shell). The group met twice prior to the workshop and provided input on the pre-workshop activities described in the following sections.

3.2 Invitee List and Agenda

The team compiled an initial list of workshop invitees, which included offshore wind energy project developers, technology developers, researchers, consultancies, government agencies, and environmental nongovernmental organizations. The steering committee reviewed the list and provided additional contacts to ensure participation from relevant experts and organizations.

The team planned the workshop for two consecutive days (Dec. 13–14, 2022) for a 2-hour period on each day. The first portion of each workshop session was devoted to an overview of workshop goals, opening remarks, presentations by experts to provide background information, and a summary of information gathered from the COPs and pre-workshop industry questionnaire. The second portion of each workshop session was devoted to gathering feedback from participants using a series of discussion questions. The complete agendas and list of discussion questions for both sessions are available in Appendix A.

3.3 Construction and Operations Plan Reviews

The team reviewed 12 COPs that were publicly available on the BOEM website (see References section), as well as the Environmental Assessment for the Lake Erie Energy Development Corporation's (LEEDCo) Project Icebreaker (e.g., Parker et al. 2018; Table 1). Keyword searches were conducted on all sections of the documents, including the main volumes and appendices. Keywords included: acoustic, noise, foundation, monitoring, attenuat*, and mitigat*. The team gathered information on foundation types, foundation characteristics, justifications for each foundation type, installation techniques, noise abatement/attenuation techniques, and monitoring strategies.

Table 1. U.S. Offshore Wind Energy Projects Reviewed

Project Name	Region
Atlantic Shores South (Formerly Atlantic Shores)	U.S. Atlantic
Coastal Virginia Offshore Wind - Commercial	U.S. Atlantic
Empire Wind	U.S. Atlantic
Kitty Hawk North	U.S. Atlantic
Maryland Offshore Wind Project	U.S. Atlantic
SouthCoast Wind (formerly Mayflower Wind)	U.S. Atlantic
New England Wind (Formerly Vineyard Wind South)	U.S. Atlantic
Ocean Wind 1	U.S. Atlantic
Revolution Wind	U.S. Atlantic
South Fork Wind Farm	U.S. Atlantic
Sunrise	U.S. Atlantic
Vineyard Wind 1 (VW)	U.S. Atlantic
LEEDCo Project Icebreaker	U.S. Great Lakes

This information was then summarized and grouped in alignment with the questions posed to industry in the pre-workshop industry questionnaire (Section 3.4). The COP review and the industry questionnaire revealed similar answers. For example, the largest number of projects are focused along the U.S. Atlantic Coast, and the monopile and impact hammering are the most common type of foundation and installation technique under consideration. The complete results of the COP review are available in Appendix B.

3.4 Pre-Workshop Industry Questionnaire

Prior to the workshop, the team distributed a brief questionnaire to all of the offshore wind energy project developers invited to the workshop. The questionnaire was designed to collect information on the specific foundation types, installation techniques, and noise abatement technologies that they are considering using in U.S. waters.

In total, 18 industry representatives completed the questionnaire. In alignment with the COP review, most respondents identified the U.S. Atlantic Coast as their primary focus for development, the monopile as the main foundation type under consideration, and impact hammering as the main installation technique under consideration. Respondents also identified the primary engineering and economic driving factors for their choice of foundation types, including water depth, seabed characteristics, supply chain availability, and production costs. The complete results of the industry questionnaire are available in Appendix C.

3.5 Mural Boards

The team facilitated group discussion and solicited feedback from workshop participants using Mural, an online collaboration platform that enables multiple users to add "sticky note" comments to an interactive digital whiteboard in real time. Participants color-coded their sticky note responses according to their group affiliation (i.e., industry, government, academia, or other) such that the responses were anonymous. The team organized the Mural board for each session into four overarching sections to guide participants throughout the workshop. Section 1 included the workshop goals, session agenda, instructions for using Mural, and a brief exercise for participants to practice adding a sticky note to the board. Section 2 summarized the results of the COP review and pre-workshop industry questionnaire to provide context for group discussions. Section 3 outlined the group discussion questions and compiled participant responses. Finally, Section 4 highlighted next steps, acknowledgements, additional resources, and organizer contact information.

4.0 Workshop Activities

The team hosted the virtual workshop on Zoom over two 2-hour sessions:

- Session 1: Foundations & Installation Methods – Dec. 13, 2022, 11 a.m.–1 p.m. ET
- Session 2: Noise Abatement & Monitoring – Dec. 14, 2022, 11 a.m.–1 p.m. ET

The following sections provide an overview of the workshop activities during each session and present brief summaries of participant feedback collected for each discussion question. The complete agendas and discussion questions for both sessions are available in Appendix A.

In total, 156 people registered for the workshop and 128 attended. Participants covered a range of sectors and included offshore wind energy project and technology developers, researchers, consultancies, government agencies, and environmental nongovernmental organizations.

4.1 Session 1: Foundations & Installation Methods

Following brief opening remarks from Nathan McKenzie (DOE) and Jill Lewandowski (BOEM), Session 1 began with two 15-minute presentations to give an overview of previous relevant work. Session 1 presentation slides and recordings are available on the Tethys website. A brief description of each presentation is provided below.

First, Ralph Grismala (ICF) presented a "Summary of Existing Foundations, Installation Methods, and Effects," highlighting results from a 2021 BOEM-funded study (ICF 2021). Descriptions were provided for a variety of foundation types, with details summarized below for the key foundation types discussed during the workshop (Figure 1). Other foundation types discussed in the presentation included tri-pile, jack-up, and floating foundations.

- Monopile foundations are single, large-diameter, steel pipes that are pile driven into the seabed. Current designs include steel monopiles of up to about 10 m (33 ft) in diameter, which are feasible in waters up to ~60 m (200 ft) deep. Monopiles are usually installed with pile-driving hammers, sometimes with vibratory methods (e.g., Tsouvalas 2020), and rarely they are drilled. Monopile installation noise may harm or displace marine animals—impact pile driving creates the largest effects, and vibratory pile driving or drilling creates smaller effects.
- Jacket foundations are lattice-truss structures similar to the designs of many offshore oil platforms. They are usually four-legged, with tubular legs at the corners and smaller-diameter horizontal cross pieces and diagonal struts. Jackets are anchored to the seabed with piles, which may be driven before placement of the jacket using a template on the seabed, driven through the tubular jacket legs, or installed through external pile guides. Jacket piles are much smaller than monopiles and the energy needed to drive them is less, thus the spatial scale of acoustic effects would be smaller than for monopiles. Note that some jackets use suction caissons.
- Tripod foundations are a tetrahedral (pyramid-shaped) space frame constructed from tubular steel members, with a cylindrical central column similar to a monopile, but it does not enter the seabed. Tripods are anchored with piles or suction caissons at the corners of the triangular base. Tripod piling has similar effects to monopiles though the spatial scale of effects would be smaller; suction caissons cause minimal acoustic effects, relative to impact pile driving.
- Suction bucket foundations have a cylinder with an open bottom and a closed top. They are lowered to the seabed through controlled flooding until the suction bucket begins to penetrate the seabed. Subsea pumps create a pressure differential by pumping water out of the suction bucket and forcing it deeper into the seabed. Suction buckets have fewer acoustic effects than monopiles due to noise-inducing activities during installation.
- Gravity foundations are structures with wide, heavy bases that sit on the seafloor and support the cylindrical central column. They are most commonly made of reinforced concrete, but steel designs are also used. Gravity foundations often require seabed preparation to create a flat and level area for the base; seabed preparation may involve dredging or the buildup of a level gravel pad. They have less intense effects than pile driving but seabed preparation requires more time with current designs.

Next, Monica Maher (DOE) presented a “Summary of Alternative Foundations and Installation Methods,” highlighting projects within the National Offshore Wind R&D Consortium (NOWRDC) and WETO project portfolios. The following four relevant projects funded by NOWRDC were discussed: (1) Texas A&M’s project on “Vibratory-Installed Bucket Foundation for Fixed Foundation Offshore Wind Towers,” (2) DEME Offshore US’s project on “Tri-Suction Pile Caisson TSPC Foundation Concept,” (3) RCAM Technologies’ project on “A Low-Cost Modular Concrete Support Structure and Heavy Lift Vessel Alternative,” and (4) Esteyco’s project on “Self-Installing Concrete Gravity-Base Substructure Sizing for 15MW Turbine.” A WETO-funded project led by Tufts on the “Effect of Fatigue on the Capacity and Performance of Structural Concrete” was also highlighted. The project is being performed in part on the basis that using concrete for offshore wind support structures avoids monopile hammering noise. It is studying implications for life span, durability, local content use, and nature-inclusive design.

Following these overview presentations, the team then presented results from the review of COPs and the pre-workshop industry questionnaire. The team then facilitated group discussion and solicited feedback from workshop participants using Mural (Figure 2). Participants were asked to add sticky notes to the board using the assigned color for their affiliation as follows: industry (purple), government (green), academia (orange), and others (yellow).

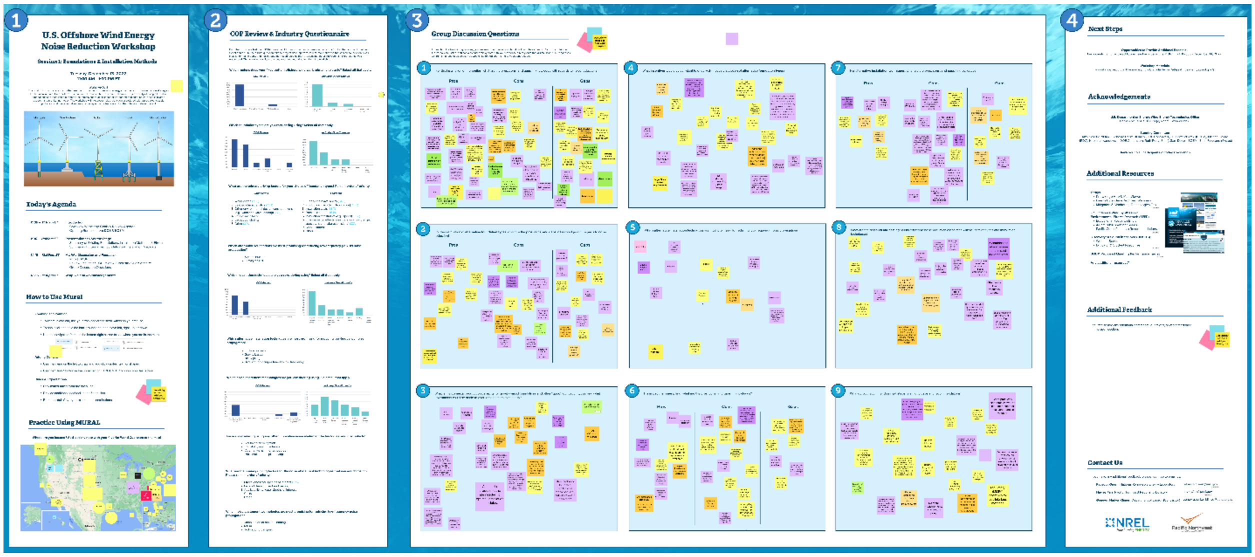


Figure 2. Screenshot of Session 1's Mural board. Click here for a high-resolution version.

In total, workshop participants provided 358 responses as individual sticky notes to the Session 1 Mural board (Figure 1) and in the webinar chat. The number of stickies and associated affiliations varied across the nine questions asked during this session, and because responses were anonymous, there was no way to verify the accuracy of affiliations. Based on the affiliations provided on the sticky notes and associated with the webinar chat, 52% of responses were from industry, 32% from "other," 14% from academia, and 2% from government. Sections 4.1.1–4.1.9 summarize the responses for each question. See this spreadsheet for all responses received.

*4.1.1 For the installation of **monopiles**, what are the **pros, cons, and gaps** in knowledge with regard to noise reduction?*

This question on monopiles received a relatively large number of comments from workshop participants, likely because monopiles are the dominant type of fixed-bottom foundation installed to date globally. A total of 66 comments were received, distributed roughly evenly across the pros (25 comments), cons (20 comments), and gaps in knowledge (21 comments) associated with monopile installation and noise reduction. Synthesized topics based on the responses are shown in Table 2. A key positive was that monopiles are a relatively proven technology with existing experience and data available to work from, including expected sound levels and efficacy of noise abatement systems. A key negative identified was high source levels and broadband energy produced with variability in effectiveness of noise reduction by frequency, particularly at low frequencies. Another negative identified was that monopiles are getting larger, and the impact energy required to drive them is increasing, such that additional noise reduction may be required to achieve current noise levels in the future, let alone to obtain further improvements. A key gap in knowledge identified was the lack of available data. The data needed covers the following topics: underwater measurement data of noise signatures, sound propagation, acoustic particle motion, substrate vibration, and the effectiveness of noise reduction technologies.

Table 2. Summary of Participant Feedback on the Pros, Cons, and Gaps in Knowledge Surrounding the Installation of Monopiles

Installation of Monopiles		
Pros	**Cons**	**Gaps**
• Relatively proven technology with existing experience and data available. • Efficient and fast installation process limiting time on water and duration of sound generation. • Monopiles are the most readily available foundation to meet demand. • Smaller benthic footprint and profile in water column than other types of foundation.	• High sound source levels and broadband energy produced. • Increasing size of monopiles into the future and increased impact energy to drive them. • Detailed soil conditions data required for planning purposes.[1] • Piling restrictions due to marine life that increase cycle times. • Uncertainties in noise and vibration effects on habitats and marine life.	• Lack of knowledge of spread of sound through soils, including challenges in abating low-frequency sound due to substrate propagation. • Lack of industry experience and supply chain for XXL[2] and larger piles. • Unknowns related to impact of noise on protected species, species density by installation location, and effectiveness of proposed noise mitigation solutions on these species. • Lack of available underwater measurement data on noise signatures and demonstrating effectiveness of mitigation measures. • Possibilities and effect of slip joints and other design optimizations from a noise perspective.

*4.1.2 For the installation of **alternative foundation types**, what are the **pros, cons, and gaps** in knowledge with regard to noise reduction?*

The alternative foundation types most often identified in feedback to this question were gravity-based foundations (GBFs) and suction buckets. A total of 48 comments were received,

---

[1] No further detail was provided during the workshop to understand how this might be different than for other foundation types.

[2] As of December 2022, XXL monopiles were considered the largest ever installed, weighing more than 2,000 tonnes each, and having a diameter of 9.5 m and a length of up to 110 m.

distributed across the pros (13 comments), cons (19 comments), and gaps in knowledge (16 comments) associated with alternative foundation types. Synthesized topics based on the responses are shown in Table 3. Two positives were among the key themes identified for these alternative foundation types regarding noise reduction. One included the potentially lower overall carbon footprint and noise-free decommissioning. For example, GBFs can be filled with sediment, lowering the carbon footprint compared to GBFs filled with concrete. A second positive identified that suction bucket foundations, where feasible, could significantly reduce noise and installation time. The suction bucket is a relatively noiseless design, as it does not require a hammer, just a pump. A key negative identified was the lack of an established supply chain, with increased uncertainty of installation timelines, and relative lack of experience with alternative foundation types compared to monopiles (although they have been used on multiple wind farms in Europe[3]). A gap identified was the very limited availability of sound data and other measurements during installation.

Table 3. Summary of Participant Feedback on the Pros, Cons, and Gaps in Knowledge Surrounding the Installation of Alternative Foundation Types

Installation of Alternative Foundation Types		
Pros	**Cons**	**Gaps**
• Non-piling methods significantly lower the acoustic footprint (particularly for lower frequencies) because they do not require a hammer. • Decommissioning noise is also potentially lower. • Reduced cycle times and carbon footprint. • Reduced installation time. • Benefit to critically endangered species by using low-noise techniques for installing foundations. • Greater labor cost versus material cost results in increased local content.	• Lack of developed supply chain increases uncertainty of installation timelines, as well as relative lack of experience. • Potentially higher non-noise environmental impacts of gravity-based foundations (e.g., benthic footprint). • Not proven across a range of soil conditions. • Potentially higher CO_2 footprint per foundation related to using concrete in GBFs, but data are lacking to quantify this comparison. • Some alternative foundation types limited by large size and fatigue performance. • Increased cost and fabrication times.	• Less experience with installation. • Lack of understanding of the impact of other non-noise environmental effects. • Lack of understanding of the noise level and characteristics associated with scour placement. • Lack of understanding of the duration and intensity of hammer requirements if final penetration not obtained. • Very limited sound data and other measurements. • Feasibility of using floating foundations in shallower water to lower noise. • Alternatives to concrete (e.g., steel) to avoid climate costs.

---

[3] For example, suction buckets have been used in offshore wind farms in Germany and Scotland, and suction buckets or caissons have been used in offshore construction for decades.

4.1.3 What is the ***domestic production capacity*** *for gravity-based foundations and other "quiet" foundation types, and what investments could be made to overcome barriers to capacity?*

A total of 32 comments were received related to the domestic production capacity for alternative foundations. Synthesized topics based on the responses are shown in Table 4. Numerous respondents felt that the domestic production capacity for alternative foundation types was essentially nonexistent, such that it would not be possible to produce the foundations domestically (as opposed to procuring them from abroad) at the rate that would be needed to meet current installation schedules. More investment in the supply chain was recommended to overcome these barriers. A key theme was the need for investments in ports to meet the space requirements for some alternatives, such as for GBFs. These upgraded ports would need to have large staging facilities, including high-capacity quay space and sufficient water depth in front of the quay, as well as a marshalling harbor to tow out the foundations. More investment in steel fabrication capacity and green concrete options was also recommended, with the need to account for differences in steel vs. concrete performance over the lifetime of the foundations and the differential carbon footprint of the materials and installation methods. Note that several of the investments identified could apply to monopiles as well, such as investment in fabrication capacity and vessels and quality control experience.

Table 4. Summary of Participant Feedback on the Domestic Production Capacity for Gravity-Based Foundations and Other Foundation Types, and the Investments Needed to Overcome Barriers

Domestic Production Capacity and Investments
• Investments in ports to meet large space requirements for some alternative foundation types—requirement for large port staging facilities, including high-capacity quay space and sufficient water depth in front of quay, as well as a marshalling harbor to tow out foundations. • Consider differences in concrete vs. steel performance over lifetime, carbon footprint, and consistent sourcing. Invest in alternative green concrete options. Invest in steel fabrication capacity. • Nonexistent domestic production capacity; cannot serially produce at the rate needed for optimal installation schedules. Invest in more supply chain systems. • Develop lease price and state incentives, e.g., to invest in infrastructure. • Investments in vessels, including specialty vessels for deployment and dredging vessels. • Consider potential use of supply chain being built for traditional fixed foundations in application to alternative foundation types. • Investments should consider that larger turbines may require larger foundations. • Determine design standards for concrete design life and resultant structure. • Quality control experience is critical; limited experience on the scale of the structures required for typical U.S. water depths.

4.1.4 What ***incentives*** *would be sufficient to effectively motivate adoption of* ***alternative foundation types****?*

A total of 39 comments were received related to identifying incentives that would effectively motivate the adoption of alternative foundation types. Synthesized topics based on the responses are shown in Table 5. A key incentive identified was providing a faster permitting timeline for noise-reducing foundations, including increased certainty that alternative foundation types will achieve positive outcomes during the COP review and National Environmental Policy Act processes. This incentive for faster permitting would need to be informed by the relative risk of reduced noise in comparison to the other potential environmental impacts of alternative foundations. Another key incentive identified was providing a guarantee of supply chain as it relates to foundation material types. Examples included the government providing sourcing material cost guarantees for steel and concrete, as well as manufacturing GBFs for turbine class and selling as a commodity. A variety of key cost reduction incentives were also identified, including lowering the cost of energy, reducing lease prices, increasing the lease length, and providing tax incentives to procure the material within the United States.

Table 5. Summary of Participant Feedback on the Incentives Needed to Effectively Motivate Adoption of Alternative Foundation Types

Incentives for Alternative Foundations
• A faster permitting timeline for noise-reducing foundations, including increased certainty that alternative foundation types will achieve a positive outcome for COP review. • Guarantee of supply chain as it relates to foundation material types, e.g, sourcing material cost guarantee by government for steel and concrete. • Cost reduction, including lowering cost of energy, reduced lease prices, and increased lease length. • Paying for the research to provide proof of technical feasibility at scale and studies on technical efficiency for technology. • For vessels, consider suspending Jones Act for offshore wind energy and/or providing shipbuilding incentives for more U.S.-flagged vessels, e.g., dredgers to do seabed preparation. • Reduced mitigation requirements during installation relative to other foundations (reducing costs), e.g., 24-hour installation allowed. • Larger local content requirements. Write local content requirements across states. • Significant bidding credits for lease sale; develop additional technical score when bidding the project, e.g., solving noise, fishery issues.

*4.1.5 Which **alternative installation techniques** are most promising for reducing low-frequency noise propagation?*

Responses regarding which alternative installation techniques are most promising for reducing low-frequency noise propagation focused on existing techniques, such as prolongation of the impulse duration and vibratory hammering (which uses low-frequency oscillations), as well as development of existing technologies, such as clump weight pile advancement. One answer noted that conducting testing and advancing development could be applied to innovative technologies. Of the 30 responses received, 19 addressed the question being asked and were further considered in analysis. Of these 19 responses, 9 were unique and the remaining 10 focused on blue piling, vibratory hammer/piling, prolongation of the impulse, and suction bucket foundations. All relevant responses are listed in Table 6.

Table 6. Summary of Participant Feedback on the Alternative Installation Techniques That Are Most Promising for Reducing Low-Frequency Noise Propagation

Alternative Installation Techniques (responses inclusive of noise abatement systems, alternative foundations, and alternative piling methods)
• Prolongation of the impulse duration (e.g., BLUE piling) • Vibratory hammer/piling (vibropiling) • Suction bucket foundations • Combination of techniques • Double bubble curtain • Resonator system (e.g., AdBm Technologies) • Drilling • Clump weight pile advancement • Floating concepts for shallow water • Strategic testing and development • Metamaterials (an engineered composite interface that attenuates low frequencies) • Low-frequency tuned noise mitigation systems

*4.1.6 For **impact hammer piling**, what are the **pros, cons, and gaps** in knowledge?*

A total of 38 comments were received related to impact hammer piling and its pros (12 comments), cons (19 comments), and gaps (7 comments) in knowledge with regard to noise reduction. Synthesized topics based on the responses are shown in Table 7. A key pro of impact hammer piling that was identified focused on the certainty of the technology, specifically certainty of permitting and its supply chain. Respondents also commented that impact hammer piling is a well-known installation technique that allows installation in a wide range of soil types and provides high certainty in the capacity of the driven pile. The level of knowledge about expected sound levels and efficacy of noise abatement systems, the databases of noise measurements, and the modeling approaches are also more developed. Comments about the benefits of impact hammer piling also mentioned its fast installation time and the flexibility of installation, referring to the ability to control the rate of piling and hammer energy to reduce the risk to pile integrity.

The cons of impact hammer piling were more varied and included environmental, technological, and regulatory themes. Noise concerns were most often mentioned within the environmental theme, and specifically the inability to effectively mitigate as piles increase in size and are embedded deeper, and the concern of noise propagation into the substrate. Other environmental concerns included the change in local habitat around a pile site and the CO_2 footprint due to diesel use during installation. In addition to the issues of noise associated with increases in pile size, several comments discussed the technological limits of increasing pile diameters. Regulatory certainty was noted as a positive aspect of using impact hammer piling and regulatory uncertainty was mentioned as a negative aspect of using impact hammer piling. The positive comment referred to permitting certainty and the negative comment mentioned that regulatory uncertainty requires unexpected mitigation that could affect timelines. This vague comment may refer to uncertainty regarding the need to add mitigation on-site if required noise reductions are not achieved, to suspend operations during conditions when an area in the vicinity of the pile cannot be monitored effectively, or to suspend operations if a protected species is detected within a certain impact radius of the piling.

Gaps in knowledge focused on the noise levels that result from the installation of piles without any noise abatement systems (unmitigated), those that result from using various noise abatement systems, and then comparing these different setups. One gap comment addressed the unknown impacts on baleen whales and the effectiveness of mitigation of the potential impacts. Others stated a lack of knowledge of sound levels of installations using larger piles and those in deeper waters.

Table 7. Summary of Participant Feedback on the Pros, Cons, and Gaps in Knowledge Surrounding Impact Hammer Piling

Impact Hammer Piling		
Pros	**Cons**	**Gaps**
• Reasonable path to regulatory certainty, with fairly well-established modeling approaches and impact assessment. • Well-established technique—can install the pile in many types of soils, even rock. • Good knowledge about expected sound levels and efficacy of noise abatement systems. • Quick, often existing supply chain from material to installation vessels. • Flexibility during installation to control piling rate and hammer energy to the degree it does not risk the pile integrity. • Fast installation time.	• Noisy installation method with environmental impacts. • Noise propagates into substrate, hampering ability to mitigate low-frequency noise, which is a particular concern for endangered species in U.S. waters. • Impact piling requires a lot of diesel for power packs, with potential CO_2 footprint implications. • Diminishing returns in noise reduction with larger piles with deeper embedment as the technology ultimately relies on creating hammer impacts. • Practical limits to hammer/pile size/installation techniques and challenges to mitigation technologies. • Material and installation failures due to driving fatigue and pile run. • Limited supply availability. • Real-time mitigation is needed and challenging. • Regulatory uncertainty due to unexpected mitigation requirements.	• Understanding noise levels from unmitigated piling and for different installation methods. • Experience and measurements when installing XXL and larger piles. • Understanding effectiveness of noise abatement systems in varying depths and of various technologies. • Understanding impacts on baleen whales and effectiveness of noise abatement in mitigating effects. • How to meet noise thresholds when piles are getting even bigger.

4.1.7 *For **alternative installation techniques**, what are the **pros, cons, and gaps** in knowledge?*

A total of 37 comments were received regarding the pros, cons, and gaps in knowledge of alternative installation techniques. A majority of the 11 positive comments referenced the potential for reduced noise levels and low-frequency propagation as a result of not impact piling. More variability existed in the 15 negative comments. Comments included concerns about the impact of continuous noise on fisheries and the habitat disturbance from alternative installation techniques. Additional concerns were expressed regarding the availability of different vessels that alternative installations would require. One issue conditioning responses in both the pro and con columns is the way the National Marine Fisheries Service (NMFS) treats continuous vs. intermittent noise, including considerations for injury criteria and behavioral and fitness impacts, for example. A key gap identified was a lack of understanding of the reliability and limitations of alternative installation techniques and the associated sound propagation profiles. Participants also identified a lack of understanding of the potential impacts on marine species, a sentiment also identified in the next question regarding research and testing needs (Section 4.1.8).

Table 8. Summary of Participant Feedback on the Pros, Cons, and Gaps in Knowledge Surrounding Alternative Installation Techniques

Alternative Installation Techniques		
Pros	**Cons**	**Gaps**
• Ability to use conventional pile systems while significantly reducing noise amplitude. • Reduced energy in piles means reduced low-frequency noise propagation, which is a problem for existing noise abatement systems. • Blue piling would seem to avoid problem with current NMFS impulsive vs. continuous behavioral harassment acoustic criteria. • Ability to install larger piles with reduced driving fatigue.	• Due to Marine Mammal Protection Act small number limits, all continuous sound techniques will severely limit the number of foundations that can be installed, compromising the commercial viability of projects. • Uncertain commercial viability due to limited availability, applicability, and track record. • Continuous noise might be better for injury criteria, but not necessarily for behavioral and fitness impacts (permanent threshold shift). • Limited vessel availability for trying out alternatives. • Prediction of vibropiling is challenging due to the interaction between soil resistance and running pile. • If more vessels are needed or vessels are on water longer, can increase vessel collision risk or other impact-producing factors.	• Understanding potential limitations of alternative techniques. • Spatial and logistical feasibility related to what to use where. • Lack of information about potential effects on biological species. • Financial implications due to different costs, timelines, and verifications. • Quantification of changes in sound propagation from alternatives. • Some alternative techniques are not state-of-the-art and need more testing offshore.

*4.1.8 What are the **research and testing needs** related to noise reduction associated with foundation types and installation techniques?*

The 29 comments regarding research and testing needs related to noise reduction associated with foundation types and installation techniques were synthesized into seven focal areas (Table 9). Environmental concerns to biological species centered around understanding how noise levels and types (continuous or impulsive) affect various species, at the individual and population scale, and what those potential effects are. Comments about installation techniques were mostly in support of more research regarding noise associated with vibropiling and impact piling together. Identified research needs that are associated with attenuation included understanding the influence of flow rate, bubble size, frequency, and the consistency of attenuation rates associated with bubble curtains. In order to understand the efficiency and effectiveness of different installation types, one comment suggested studying the potential influence of operator experience, and another requested more research into vessel needs for each foundation type. In addition, several comments requested more holistic demonstrations, which include comparison of mitigated and unmitigated installations, and examining other potential impacts of installation in addition to noise. Comments similar to these and to the one comment about data sharing were also noted in the next question regarding next steps (Section 4.1.9).

Table 9. Summary of Participant Feedback on the Research and Testing Needs Related to Noise Reduction Associated With Foundation Types and Installation Techniques

Research and Testing Needs
• Environmental: Behavioral responses of biological species to impulsive and continuous noise, population consequences, and definitions of impact to sensitive receivers. • Spatial/temporal deconfliction with sensitive species: Research on proper installation time slots/periods that would not affect marine mammal migrations or their habitat. • Installation techniques: Combinations of techniques, alternatives to hammers and associated effects, e.g., combination of vibratory hammer and impact hammer head. • Factors that affect attenuation at different frequencies. • Factors that affect operational efficiencies and effectiveness. • Understanding other impact-producing factors aside from noise to provide a more holistic assessment of potential environmental effects (e.g., change in vessel collision risk if there are more vessels or vessels are on the water longer) and providing impact definitions, such as for resilience. • Various types of demonstrations: Full-scale technology demonstration; need to allow more unmitigated installations for comparison. • Data sharing considerations, which may differ for raw versus processed data.

*4.1.9 What do you recommend as **next steps** relating to gaps and recommendations?*

The 34 comments regarding next steps were synthesized into five focal areas: research needs, information management, regulatory considerations of biological species, regulatory process certainty, and resolution of concerns in installation techniques. The 11 comments about research needs were varied, with only two ideas receiving multiple support: more research into vibropiling and comparing the noise levels from mitigated and unmitigated installations in the same conditions. Verbal comments during the workshop echoed the written comments regarding information management—primarily the need to improve data sharing—and offered an industry conference as a forum to do so. It was suggested that a joint industry forum could be used to pool resources and undertake strategic monitoring/initiatives, which could then also make results available in a timely manner. A majority of comments about regulatory considerations of biological species suggested that the NMFS acoustic thresholds should be revised and that the timing, installation type, and potential impact should be considered in these revisions. The synthesized focal area of regulatory process certainty included comments about the need for regulatory drivers, incentives, and certainty for continued research, development, and adoption of new technologies. The few comments in the focal area of installation techniques were technology-specific and offered things to consider rather than concrete next steps.

Table 10. Summary of Participant Feedback on Next Steps Relating to Gaps and Recommendations Related to Offshore Wind Noise Reduction

Next Steps
• Broadly, further research is needed on noise abatement and installation technique variations and their environmental impacts. • Cost/benefit analysis environmental impacts for foundations and installation methods. • Regulatory drivers and incentives for development and adoption of quieter alternatives and installation methods. • Make more measurements on vibropiling and explore its options (frequency, etc.). • Research the options for improvement of the marine environment, by introducing nature-inclusive design/fish shelter/reefs/reef building species to the foundations. • Information gathering, organizing, and sharing. • Regulatory considerations for biological species and how to assess and permit continuous noise sources—e.g., need to revisit NMFS' take thresholds and approach if vibropiling is to be incentivized. • Certainty around the current regulatory process to be able to get the industry started with the current domestic/state content requirements and deploy 30 GW by 2030. • Resolution of concerns in installation techniques—e.g., current vibropiling method requires change-out of equipment offshore, which takes a lot of vessel time and is a critical operation.

4.2 Session 2: Noise Abatement & Monitoring

Session 2 also began with two 15-minute presentations to set the stage. Session 2 presentation slides and recordings are available on the Tethys website. A brief description of each presentation is provided below.

First, Samuel Denes (BOEM) presented an "Overview of Noise Monitoring and BOEM's Proposed Received Level Target," building on the summary document provided to workshop registrants as pre-workshop reading. Three classes of wind farm acoustic monitoring were identified, including long-term acoustic recordings from the lease area (over the course of a few years), acoustic monitoring for mitigation (to identify whether there are vocalizing species present), and sound field verification for limited foundations (to determine whether the modeled analyses encompass the realized sound fields). Sound field verification requirements are determined on a per-project basis, but currently there is a lack of predictability, as well as variability in methodology. The proposed target for noise production seeks to determine a goal for the level of noise generated during impact pile driving that is understandable, meaningful, aspirational, and measurable. Based on data from the COPs, there are many factors that can influence the predicted ranges of noise generated during installation (e.g., pile diameter, hammer size, number of strikes, sediment characteristics, seasonality, modeling conservatism, number of piles, and foundation type). There are existing data on predicted noise levels from the COPs, on measured noise levels from construction of existing wind farms in the United States and Europe, and on demonstrating the effectiveness of different mitigation strategies. BOEM's proposed received level target aims to reduce the effects of greatest concern and considers criteria of interest, including cumulative sound exposure level for low-frequency cetaceans and peak sound pressure level for high-frequency cetaceans. The proposed target is a received level at 1 km, which is below Level A harassment criteria (as specified in NMFS Technical Guidance) and is based on acoustic measurements (i.e., explicitly does not consider animal movement).

Next, Michael Bellmann (itap [Institut für technische und angewandte Physik GmbH]) gave a presentation titled "Noise Abatement/Mitigation Systems for Impact Pile-Driving - Technical Overview and Offshore Experiences," which highlighted results from Bellmann et al. (2020) and recent updates. The history of underwater noise regulation in Germany includes impulse noise (since 2011) and their noise mitigation concept (2013). In Germany, there are currently 21 offshore wind farms and 28 single-installation projects; all available noise mitigation systems and noise abatement systems have been tested in German waters. Research was funded by the German regulator BSH (2016–2019) based on their underwater noise database MarinEARS; this research aimed to investigate influencing factors on unmitigated pile-driving noise and to provide lessons learned regarding noise mitigation concepts. The output of the research summarized legal requirements, identified site-specific and project-specific factors influencing pile-driving noise, and defined state-of-the-art noise mitigation concepts (Bellman et al. 2020). Noise mitigation measures include noise reduction by avoiding underwater noise (i.e., noise mitigation systems) and reducing existing underwater noise (i.e., noise abatement systems). Primary noise mitigation strategies include reduced impact pile-driving energy, vibropiling (continuous noise), suction buckets, gravity foundations, blue piling hammer, and new hammer technologies. Noise abatement systems include bubble curtain systems, "shell in shell" systems, and a variety of other systems. The advantages, disadvantages, and readiness of the various noise mitigation and abatement systems were presented. For noise mitigation systems, there are currently limited available options, and each option requires project-specific adaptation/optimization. For noise abatement systems, several options are ready for offshore use, with the achievable overall noise reduction being highly frequency dependent.

Following these overview presentations, the team then facilitated group discussion and solicited feedback from workshop participants using Mural (Figure 3). Participants were again asked to add sticky notes to the board using the assigned color for their affiliation as follows: industry (purple), government (green), academia (orange), and other (yellow).

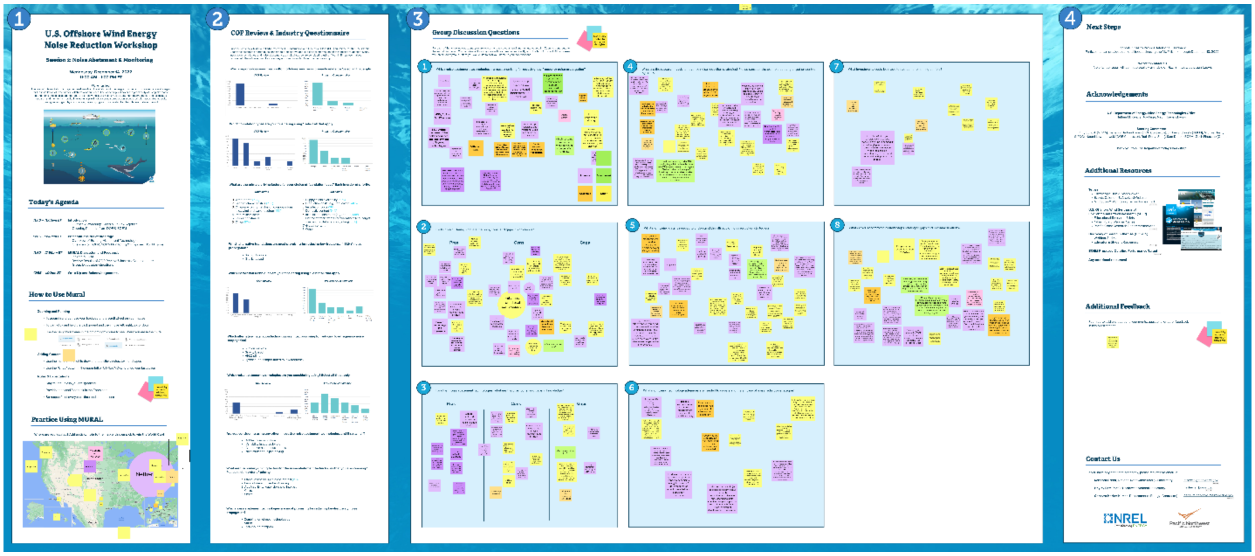


Figure 3. Screenshot of Session 2's Mural board. [Click here for a high-resolution version.]

In total, workshop participants provided 243 responses as individual sticky notes on the Session 2 Mural board (Figure 3) and in the webinar chat. The number of stickies and associated affiliations varied across the eight questions asked during this session, and because responses were anonymous, there was no way to verify the accuracy of affiliations. Based on the affiliations provided on the sticky notes and associated with the webinar chat, 50% of responses were from industry, 36% from "other," 10% from academia, and 4% from government. Sections 4.2.1–4.2.8 summarize the responses for each question. See this spreadsheet for all Session 2 responses.

4.2.1 *Which noise abatement technologies are most promising for reducing low-frequency noise propagation?*

Workshop participants identified a wide variety of noise abatement technologies they believe are the most promising for reducing low-frequency noise propagation, including the AdBm Noise Mitigation, Double Big Bubble Curtain, and Hydro Sound Damper. A total of 33 comments were received; synthesized topics are shown in Table 11. Many respondents highlighted that a combination of technologies would be needed. A few respondents also noted that modifying pile driving or using alternative foundations that do not require pile driving (e.g., suction buckets) could be promising alternatives. Unfortunately, few comments provided the reasoning behind their answers, although much of this detail can be found in the responses to the next two questions (Sections 4.2.2 and 4.2.3).

Table 11. Summary of Participant Feedback on the Noise Abatement Technologies That Are Most Promising for Reducing Low-Frequency Noise Propagation

Promising Noise Abatement Technologies
• AdBm noise mitigation system • Double Big Bubble Curtain (DBBC) • Hydro Sound Damper (HSD) • A combination of noise abatement technologies • Big Bubble Curtain (BBC) • Enhanced Big Bubble Curtain (eBBC) • Noise Mitigation Screen (e.g., IHC Offshore Systems)

- Modifying pile driving (e.g., smaller pile diameter, reducing tip resistance and friction)
- New hammer technologies (e.g., PULSE, MENCK Noise Reduction Unit)
- New installation alternatives (e.g., suction buckets) not using pile driving
- Additional noise abatement technologies currently under development

4.2.2 For bubble curtains, what are the pros, cons, and gaps in knowledge?

A total of 42 comments were received related to bubble curtains and their pros, cons, and gaps in knowledge with regard to noise reduction. Synthesized topics based on the responses are shown in Table 12. Overall, workshop participants consider bubble curtains to be a proven technology with an extensive deployment history demonstrating reliability and efficiency at reducing high-frequency noise. Additionally, bubble curtains can be paired with other noise abatement technologies, are relatively easy to deploy, and are generally well known and accepted by regulators. Key cons identified by workshop participants are that bubble curtains are sensitive to environmental conditions and that they create high CO_2 emissions (diesel compressors). Finally, remaining knowledge gaps identified by participants include studies to explore the effectiveness of bubble curtains in different environments and at different frequencies, as well as standard methods and guidelines to achieve noise reduction.

Table 12. Summary of Participant Feedback on the Pros, Cons, and Gaps in Knowledge Surrounding Bubble Curtains

Bubble Curtains		
Pros	**Cons**	**Gaps**
• Proven technology with extensive deployment history demonstrating its efficiency and reliability. • Pairable with other close-to-pile abatement methods (e.g., AdBm/HSD). • Easy to deploy relative to other noise abatement technologies. • Vessels are likely available to perform this work.	• Efficiency is sensitive to environmental conditions (e.g., currents, depth). • Uses a lot of fuel and creates the highest CO_2 emissions of all available systems. • Extra vessel(s) inducing higher costs compared to the near-field systems.	• Studies to explore effectiveness at low frequencies. • Lack of guidelines to achieve noise reduction and spur investment. • Studies to quantify noise reduction in different environments. • Studies to explore the effectiveness of BBCs with large-diameter piles.

4.2.3 For other noise abatement technologies, what are the pros, cons, and gaps in knowledge?

A total of 46 comments were received related to other noise abatement technologies. Synthesized topics based on the responses are shown in Table 13. The main advantages of other noise abatement technologies identified by workshop participants include their relative ease of deployment (in terms of vessel and power use) and their ability to be paired with other systems. Unfortunately, few responses identified the specific noise abatement technology they refer to. A couple of comments specifically highlighted the pros of AdBm systems, which can use additional resonators to improve performance, can respond to changes in regulations or sound source spectra, and do not need to be replaced. Key cons identified by workshop participants include the commercial availability of the technologies/supply chain and that some technologies are not effective enough on their own. Finally, remaining knowledge gaps identified by participants include studies to explore effectiveness at low frequencies and studies to be used for quantification of noise reduction in impact modeling. A key theme highlighted as both a con and gap is uncertainty around regulator perception and acceptance or, essentially, how regulators will treat less common or new technologies in their analyses.

Table 13. Summary of Participant Feedback on the Pros, Cons, and Gaps in Knowledge Surrounding Other Noise Abatement Technologies

Other Noise Abatement Technologies		
Pros	**Cons**	**Gaps**
• Ease of deployment (e.g., vessels, power). • Can be paired with BBC, DBBC, and other technologies. • AdBm systems do not need to be replaced and can add resonators to improve performance and respond to changes in regulations or sound source spectra.	• Limited experiences examining effectiveness at depth. • Commercial availability of the technologies/supply chain. • Differential need to replace worn out elements, depending on types of noise abatement technology. • Cannot capture much of the “ground coupled” sound pressure.	• Demonstrations in U.S. waters. • Uncertainty around regulator perception and acceptance. • Studies to explore effectiveness at low frequencies.

4.2.4 What are the research needs to advance noise reduction strategies? Please consider the example quieting target presented by BOEM.

A total of 29 comments were received related to the research needed to advance noise reduction strategies. Synthesized topics based on the responses are shown in Table 14. Comments on the research needs to advance noise reduction strategies favored studies addressing the physiological and behavioral response of marine fauna to underwater noise and substrate-borne vibration generated during installation activities. For instance, dose-response curves for particular species of concern and tuning of allowable noise exposure levels on a species basis were mentioned. A second consistent theme that emerged was research comparing and quantifying noise emissions from the different alternative installation methods and materials in contrast to impact piling. Similarly, suggestions were also made for research to quantify the efficacy of different noise reduction strategies with and without noise abatement (e.g., reference piles) in the same construction environment. No comments directly addressed the BOEM quieting target, although a few suggestions noted the need for research to improve the NMFS acoustic criteria for temporary and permanent threshold shifts (TTS and PTS, respectively) under the urgency of the current construction timeline but did not offer specific recommendations or study details.

Table 14. Summary of Participant Feedback on the Research Needs to Advance Noise Reduction

Research Needs
• The effects of installation sounds and substrate vibration on animals (physiological and behavioral response). • The noise generated by alternative installation methods and materials (e.g., hydraulic, screw, suction buckets). • Comparative studies that quantify effects of noise reduction methodologies with/without mitigation (reference piles). • Relevance of current TTS and PTS criteria and how to improve within the current construction time frame.

4.2.5 What monitoring data are needed to understand the efficacy of noise reduction strategies?

A total of 25 comments were received on the monitoring data needed to understand the efficacy of noise reduction strategies. Synthesized topics based on the responses are shown in Table 15. A dominant theme in the suggestions for monitoring data pointed to a lack of consistency and standardization for measurements. Several suggestions called out a need for standardization of monitoring protocols that are consistent with existing or historical measurements in both the near and far field, are transferable between projects, and can be used to inform acoustic propagation models. Some recommendations included references to International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) standards development. Additionally, workshop participants suggested that concurrent environmental data should also be collected during installation activities to help contextualize noise levels (e.g., sound contributions of surface wind noise, waves, and currents to background levels), biological data that may help inform animal behavioral response (e.g., prey availability), and geophysical data that helps characterize the site and provides details for sound propagation effects (e.g., bathymetry, soil type, and substrate layers). Similar to suggestions in section 4.2.4, parallel noise measurements of mitigated and unmitigated pile driving in identical environments (i.e., within the same construction or lease area) will help to quantify the performance of noise abatement technologies and provide important validation measurements for propagation models. Sound source data were also recommended for data collection to address source-level validation of back-calculated source levels to better understand noise reduction strategies. Finally, a key theme was identified related to the need for open access and the transfer of noise installation data between construction projects to help facilitate acceptance and reduce uncertainties in model outputs.

Table 15. Summary of Participant Feedback on the Monitoring Data That Are Needed to Understand the Efficacy of Noise Reduction Strategies

Monitoring Data Needs
• Consistent, standardized measurements that are transferable between projects. • Environmental data (e.g., wind, current, waves), biological contextual data (e.g., prey availability), and physical site characterization data (e.g., bathymetry, soil type, substrate layers). • Parallel noise measurements for comparisons of mitigated and unmitigated/reference pile driving in the same environment that also informs propagation models. • Acoustic measurements that can inform propagation models for back-calculated source-level estimation. • Open access and transfer of installation noise monitoring data between projects.

4.2.6 What monitoring technology advances are needed to understand the efficacy of noise reduction strategies?

A total of 14 comments were received related to the monitoring technology advances that are needed to understand the efficacy of noise reduction strategies. Synthesized topics based on the responses are shown in Table 16. Respondents understood the question as referring primarily to the receptor side of the model—addressing behavioral and physiological responses of marine animals to changes in noise. In particular, advances are needed in optical, acoustic, thermal, and tagging technologies to track behavioral and physiological response of animals, as are advancements in stress hormone techniques that include breath and fecal sampling. Autonomous systems (anchored buoys) and mobile sensor platforms (gliders, drones) were also identified as areas for technology advancement for monitoring animal responses. Another suggestion scaled up from technologies that monitor or track a single animal or groups of animals, to the development of a better understanding of population-level consequences. Suggestions were also included for technology improvements for passive acoustic monitoring (PAM), including array designs, sensor endurance, and requirements for recording times (how long is long enough). A standardized technology and approach for measuring acoustic particle motion and substrate vibration was also put forward as a pressing need. Methods and technology for consistent, standardized measurements (similar to section 4.2.5) that can be compared with propagation model outputs and shared between projects also emerged as an important need. Lastly, suggestions were made for advances in efficiency for processing and analyzing large data sets, both archival and real-time, that reduce costs while providing meaningful results.

Table 16. Summary of Participant Feedback on the Monitoring Technology Advances That Are Needed to Understand the Efficacy of Noise Reduction Strategies

Monitoring Technology Advances Needed
• Advancements in standardized technologies and methods for animal detection and tracking to assess behavioral responses (visual, acoustic, thermal) and physiological responses (stress). • Improvements in instrumentation and measurement approach for monitoring near- and far-field water column and substrate acoustic disturbance. • Complete comparisons between model results and in situ measurements. • Provide consistent, standardized measurements that are transferable between projects to help evaluate efficacy. • Continue to advance methods and research to investigate noise effects on animals and population consequences. • Standardization and advances in efficiency for processing and analysis of large data sets (archival and real-time).

4.2.7 What investments could be made to overcome remaining barriers?

A total of 13 comments were received on recommended investments to overcome remaining barriers. Synthesized topics based on the responses are shown in Table 17. The suggested investments indicated that progress toward establishing consistent methodologies, along with new technologies, for noise abatement and modeling would help to overcome some of the barriers to ongoing development and installation of new turbines. The ability to have guidance and agreement from regulators based on clear, standardized, and transparent methodologies and expectations would be helpful. Being able to have data available and accessible to multiple developers would also allow for increased transparency and data consistency to be leveraged for different projects with similar constraints. Also suggested were additional investments and investigations into alternative technologies, including an emphasis on lower frequency and unexplored options for minimizing particle motion and substrate vibration. A clear theme among the comments was a desire to have regulators provide consistent guidelines and expectations for benchmarks, noise reduction goals, and updated acoustic thresholds for harassment and species-specific impact. Suggestions also included incentivizing noise reduction efforts and accepting new technology advancement and utilization.

Table 17. Summary of Participant Feedback on Potential Investments That Could Be Made to Overcome Remaining Barriers

Potential Investments
• Develop new technologies and establish consistent methodologies, including addressing emerging topics like particle motion. • Invest in providing data consistency, transparency, and ease of access to the best available science. • Encourage different regulatory considerations, evaluations, and possible incentivization for industry to advance and adopt new technologies or methods for reducing noise. • Support supply chain and technology access and availability in the United States.

4.2.8 What do you recommend as next steps related to gaps and recommendations?

A total of 28 comments were received on recommended next steps related to filling gaps and other recommendations. Synthesized topics based on the responses are shown in Table 18. The most evident theme for the suggested next steps was to have collaborative meetings and workshops between industry, regulators, and other stakeholders. These would not only be used to collectively establish consistent guidelines, goals, and expectations for noise reduction and targets but also to explore alternative methodologies, approaches, and new technology development and application based on feasible, practical, and achievable benchmarks. Regulatory evaluation of acoustic thresholds for behavioral response and frequency-specific noise concerns were also recommended. Additionally, there were calls to establish consistent data standards and methods for data to be shared and made accessible to the greater community. Three of the 28 comments also specifically indicated that Joint Industry Projects (JIPs) could be used to address and advance many of the topics of concern.

Table 18. Summary of Participant Feedback on Recommended Next Steps

Next Steps
• Hold a meeting between regulators, industry members, and other stakeholders to establish noise reduction requirement goals and expectations as well as consistency for models, approaches, and standards necessary for permitting. This includes looking ahead to setting noise reduction targets and the application of noise quieting technologies. • Initiate a collaboration to establish consistent approaches for noise measurements, model development, and testing new applications or methods. Means to address this include establishing JIPs. • Provide increased access to information on species impacts, measurement data, and the best available science. • Develop regulatory considerations, evaluations, and incentivization for adopting and advancing new technologies or methods.

- Invest in development and continued refinement of noise abatement and mitigation technologies; continue to evaluate cost and efficacy options for noise quieting technologies.

5.0 Discussion and Conclusions

The joint lab team synthesized over 600 participant comments from the workshop sessions. In addition to research topic needs, crosscutting topics from both workshop sessions included the need for improved data access, sharing, and transparency, and additional opportunities for disseminating the best available science and expertise related to noise reduction strategies. These topics were not addressed in the pre-workshop questionnaire or the COP review. Forums to address data sharing and exchange of the best available science should include all stakeholders (e.g., industry, academia, environmental nongovernmental organizations, regulators).

Based on the team's synthesis of workshop feedback, four overarching research and development (R&D) themes were identified related to noise and vibration reduction strategies in U.S. waters, including evaluation of efficacy and costs, providing support for supply chains, developing standards, and understanding effects on wildlife. Each R&D theme is listed below, with paraphrased comments from participants provided as support. The bulleted comments are examples of what participants said, but as they were single points they have added to the wider recommendations rather than being identified as major themes individually.

- Evaluate **efficacy and costs** of existing and innovative piling approaches and alternative foundation types, as well as available and novel noise abatement technologies.
    - Assess technical feasibility and efficiency at scale for new technologies.
    - Perform offshore testing of available and alternative technologies and gather field data on sound propagation at different frequencies and in different environments (e.g., depth, substrate types, hydrodynamic conditions).
    - Collect data on underwater sound signature characterization, sound propagation, and acoustic particle motion, and data that demonstrate the effectiveness of piling approaches and noise reduction technologies.
- Provide support for the U.S. **supply chain** to increase access and availability in the United States for alternative foundations and noise abatement technologies.
    - Consider differential CO_2 footprints of alternative foundation types (e.g., gravity-based, concrete vs. steel) and installation methods and how to minimize for long-term ancillary impact.
    - Estimate availability of materials (e.g., steel fabrication capacity, concrete) for manufacturing alternative foundation types.
    - Determine the investments needed for ports to meet the space requirements for certain alternative foundation types (e.g., gravity-based foundations require a large marshalling harbor).
    - Understand the investments needed in vessels for installing each foundation type.
- Address the need to develop **standards** to help provide consistency across models and approaches for alternative foundations, quieting technologies, and monitoring.
    - Establish and create opportunities to improve and develop sound propagation models, including the incorporation of mitigating measures.

    - Determine design standards to be used as reference points for concrete life and resultant structures.
    - Invest in testing standards for new low-CO_2-emission cement formulas.
- Understand potential effects on **wildlife** from piling noise, including acoustic sound pressure for marine mammals, waterborne acoustic particle motion for fishes, and substrate-borne vibration for seafloor boundary fishes and invertebrates, as well as the potential cumulative effects from installation of alternative foundation types.
    - Determine potential behavioral and physiological effects on marine mammals and other sensitive species (e.g., fishes, invertebrates) from impulsive vs. continuous noise.
    - Understand species density at each site and the effectiveness of proposed noise mitigation solutions on these species, including cumulative effects from multiple turbines/wind farms.
    - Investigate the effect on benthic and fish communities from various foundation types and changes in sediment dynamics.
    - Perform cost/benefit analysis of environmental impacts for foundations and installation methods.

The R&D themes were also informed by the foundational knowledge gained from the pre-workshop industry questionnaire and COP review. The efficacy and costs R&D theme encompasses questions from the questionnaire and COP review related to foundation types, installation techniques, and noise abatement technologies. The questionnaire and COP review also showed that the choice of foundation types used in projects was influenced by the geophysical considerations of water depth, seabed characteristics, and wind/wave loading, but that other considerations, such as familiarity with a particular foundation type, also played a role. Comments from the workshop supported the importance of these factors and identified knowledge gaps. For example, more field data collection was requested on noise propagation resulting from alternative foundations in different environments (e.g., across depths, substrate types, and hydrodynamic conditions). The questionnaire responses substantiated that alternative installation techniques are being considered by developers, namely vibropiling, pulse duration prolongation, and drilling. Workshop discussions regarding the current state of these technologies, their advantages, disadvantages, and knowledge gaps were plentiful. However, alternative installation techniques, as well as alternative foundations and noise abatement technologies, were limited in the COP review. This is unsurprising, as COPs summarize actual construction plans that are often based on methods previously employed by the developer. COPs are not a forum that developers have used to elaborate on innovative and unproven technologies. Regarding noise abatement alternatives, the questionnaire and COP review showed that similar technologies are being considered by developers: single bubble curtain, double bubble curtain, hydrosound damper, noise mitigation screen, and other damping systems. Discussions of these were greatly expanded upon in the workshop, and more proprietary systems such as AdBm were also discussed, as were opinions on their advantages and disadvantages. Many comments highlighted the need for more data on their efficacy in certain environmental conditions and when used in combination with different installation techniques.

The efficacy, costs, and supply chain R&D themes synthesized from the workshop comments were supported in the questionnaire and COP review. These activities identified the importance of supply chain and costs in the selection of foundation types. Participant comments identified the importance of the supply chain and noted that more information is needed to understand material, vessel, and port requirements when considering alternative foundations.

The standards setting and wildlife R&D themes were not addressed in depth in the questionnaire or in the COP review. However, wildlife considerations were considered in one question that asked what the primary driving factors are for selecting noise abatement technologies. Both the questionnaire and COP review recognized that effectiveness for species of interest was the top factor, particularly for endangered baleen whales that are a focus of conservation efforts in North America. The workshop participants had discussions regarding potential behavioral, physiological, and population-level impacts on species of concern and the regulatory acoustic impact levels established.

After the R&D themes were synthesized from comments, the questionnaire, and the COP review, opportunities for investments within each theme were identified to fill knowledge gaps and advance the development of existing and innovative technologies as well as strategies for noise reduction during offshore wind construction in U.S. waters (Table 19). As identified by several workshop participants, future funding opportunities for research should consider joint ventures and public/private partnerships (e.g., JIPs) for advancing (across lease areas, foundation designs, and installation techniques) with measurement collection, monitoring, model development, and different noise reduction systems.

Table 19. Key R&D Themes and Recommendations for Future Work

R&D Theme	Recommendations
Evaluate **efficacy and costs** of existing piling approaches and available noise abatement technologies, and of alternative foundation types, innovative piling approaches, and novel noise abatement technologies	• Conduct a literature review and synthesis of best available science related to noise and vibration reduction strategies in the United States and elsewhere • Fund comparative desktop and experimental studies that quantify: - Effects of using different noise mitigation and abatement techniques - Effects of novel solutions on sound/vibration propagation - Other environmental effects (e.g., on habitat, CO_2 emissions, vessel availability, supply chain) • Explore existing and novel funding mechanisms to spur innovation and support future investments
Provide support for **supply chain** as well as technology access and availability in the United States for alternative foundations and noise abatement technologies	• Scope investments to advance the mass manufacturing of alternative foundation types • Explore existing and novel funding mechanisms to ensure supply chain development
Develop **standards** for alternative foundations, quieting technologies, and monitoring	• Host workshop(s) or engage in other efforts, as needed by BOEM, to solicit technical information for establishing standards and benchmarks • Provide guidance and investments for consistent data collection, sharing, and access

	- Invest in design and testing standards for foundation materials, including lower CO_2 emission formulas
Understand potential impacts on **wildlife** from piling noise and substrate-borne vibration, as well as the potential cumulative environmental effects from the installation of alternative foundation types	- Fund research studies on the potential behavioral and physiological effects of installation noise, particle motion, and substrate vibration on key marine species - Support monitoring and invest in new approaches and technologies (e.g., autonomous systems) - Provide opportunities for knowledge exchange

Overall, a high level of interest was expressed in the workshop as evidenced by the level of engagement and feedback provided. The workshop thus provided a novel opportunity for significant exchange of information among participants from several different sectors. Participants identified a variety of opportunities for next steps toward noise reduction of offshore wind turbine installation in U.S. waters, including recommendations for future investments to provide certainty in the use of new technologies associated with alternative foundation types, noise abatement systems, and efficacy monitoring.

References

Atlantic Shores Offshore Wind. 2021. “Construction and Operations Plan: Atlantic Shores Offshore Wind”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/atlantic-shores-offshore-wind-construction-and-operations-plan.

Bellmann, M.; May, A.; Wendt, T.; Gerlach, S.; Remmers, P.; Brinkmann, J. (2020). *Underwater Noise During Percussive Pile Driving: Influencing Factors on Pile-Driving Noise and Technical Possibilities to Comply With Noise Mitigation Values.* Report by Institute of Technical and Applied Physics (itap) GmbH. https://www.itap.de/media/experience_report_underwater_era-report.pdf.

Dominion Energy Services, Inc. 2021. “Construction and Operations Plan: Coastal Virginia Offshore Wind Commercial Project”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/cvow-construction-and-operations-plan.

Empire Offshore Wind, LLC. 2022. “Empire Offshore Wind: Empire Wind Project (EW1 and EW2) Construction and Operations Plan”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/empire-wind-construction-and-operations-plan.

Fried, Samantha, Desen Ozkan, Katarina Halldén, Bridget Moynihan, John DeFrancisci, Dan Kuchma, Chris Bachant, and Eric Hines. 2022. *Low-Carbon, Nature-Inclusive Concrete Gravity-Based Foundations for Offshore Wind Turbines*. OSPRE Report 2022-02. https://dl.tufts.edu/pdfviewer/t722hq84r/pk02cr377.

ICF. 2021. *Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations*. Sterling, VA: U.S. Dept. of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2021-053. https://www.boem.gov/sites/default/files/documents/environment/Comparison-Environmental-Effects-Different-OWT-Foundations-2021.pdf.

Kitty Hawk Wind, LLC. 2022. “Construction and Operations Plan: Kitty Hawk Wind”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/kitty-hawk-north-wind-construction-and-operations-plan-commercial.

Mayflower Wind Energy LLC. 2022. “Mayflower Wind: Construction and Operations Plan”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/Mayflower%20Wind%20COP%20Volume%20I_0.pdf.

Musial, W., Spitsen, P., Duffy, P., Beiter, P., Marquis, M., Hammond, R. and Shields, M., 2022. *Offshore Wind Market Report: 2022 Edition.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-83544. https://www.energy.gov/sites/default/files/2022-09/offshore-wind-market-report-2022-v2.pdf

Ocean Wind. 2022. “Construction and Operations Plan: Ocean Wind Offshore Wind Farm”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/ocean-wind-1-construction-and-operations-plan.

Park City Wind, LLC (New England Wind). 2022. “Construction and Operations Plan: Lease rea OCS-A 0534”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/new-england-wind-ocs-0534-construction-and-operations-plan.

Parker, R.; Kerwin, K.; Kozlowski, D.; Wheatley, K.(2018). *Final Environmental Assessment LEEDCo Project Icebreaker Lake Erie, City of Cleveland, Cuyahoga County, Ohio.* Golden, CO: U.S. Department of Energy Golden Field Office. DOE/EA-2045. https://tethys.pnnl.gov/publications/final-environmental-assessment-leedco-project-icebreaker-lake-erie-city-cleveland.

Revolution Wind. 2022. “Construction and Operations Plan: Revolution Wind Farm” Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/revolution-wind-farm-construction-and-operations-plan.

South Fork Wind. 2021. “Construction and Operation Plan: South Fork Wind Farm”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/south-fork.

Sunrise Wind. 2022. “Construction and Operation Plan: Sunrise Wind Farm Project”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/sunrise-wind-construction-and-operation-plan.

The White House. 2021. FACT SHEET: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs. https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/.

Tsouvalas, A., 2020. Underwater noise emission due to offshore pile installation: A review. *Energies*, 13(12), p.3037. https://tethys.pnnl.gov/publications/underwater-noise-emission-due-offshore-pile-installation-review

US Wind. 2022. “Construction and Operation Plan: Maryland Offshore Wind Project”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/renewable-energy/state-activities/us-wind-construction-and-operations-plan.

Vineyard Wind LLC. 2018. “Draft Construction and Operation Plan”. Submitted to the Bureau of Ocean Energy Management. https://www.boem.gov/webteam/Vineyard%20Wind/Vineyard-Wind-COP-Vol-I-Project-Info.pdf

Appendix A: Workshop Agenda & Discussion Questions

Session 1: Foundations & Installation Methods – December 13, 2022, 11 a.m.–1 p.m. ET

Introduction (11:00–11:10 a.m. ET)	
Overview workshop goals and review agenda (Moderator; 5 minutes) Opening remarks from DOE and BOEM (Nate McKenzie and Jill Lewandowski; 5 minutes)	
Presentations to Set the Stage (11:10–11:45 a.m. ET)	
Summary of Existing Foundations, Installation Methods, and Effects (Ralph Grismala, ICF)	15 minutes
NOWRDC - Alternative Foundations and Installation Methods (Monica Maher, DOE)	15 minutes
Break	5 minutes
Mural Discussion and Feedback (11:45 a.m.–12:50 p.m. ET)	
Introduction to Mural	5 minutes
Review Results of Pre-Workshop Industry Questionnaire	5 minutes
Discussion Questions 1. For the installation of **monopiles**, what are the **pros, cons, and gaps** in knowledge with regards to noise reduction? 2. For the installation of **alternative foundation types**, what are the **pros, cons, and gaps** in knowledge with regards to noise reduction? 3. What is the **domestic production capacity** for gravity-based foundations and other “quiet” foundation types, and what investments could be made to overcome barriers to capacity? 4. What **incentives** would be sufficient to effectively motivate adoption of **alternative foundation types**? 5. Which **alternative installation techniques** are most promising for reducing low-frequency noise propagation? 6. For **impact hammer piling**, what are the **pros, cons, and gaps** in knowledge? 7. For **alternative installation techniques**, what are the **pros, cons, and gaps** in knowledge? 8. What are the **research and testing needs** related to noise reduction associated with foundation types and installation techniques? 9. What do you recommend as **next steps** relating to gaps and recommendations?	60 minutes
Wrap-Up and Acknowledgements (12:55–1:00 p.m. ET)	
Close out Session 1 and discuss next steps (Moderator; 5 minutes)	

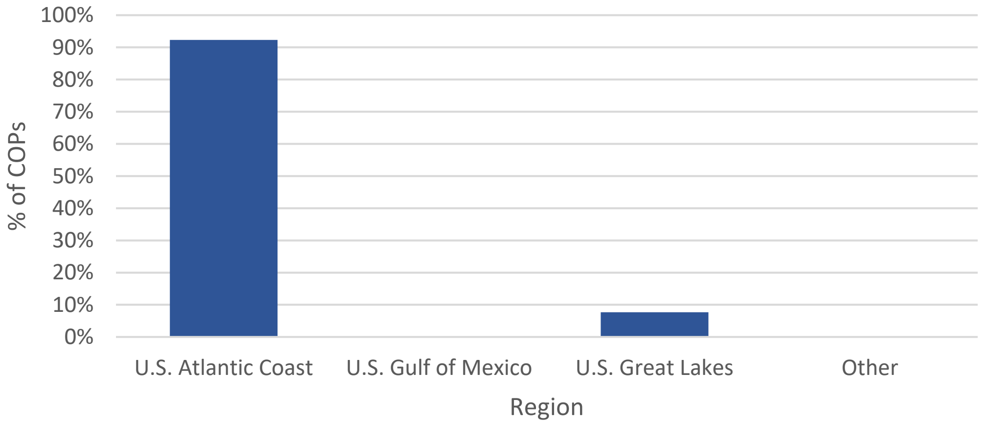
Session 2: Noise Abatement & Monitoring – December 14, 2022, 11 a.m.–1 p.m. ET

Introduction (11:00–11:10 a.m. ET)	
Overview workshop goals; Review agenda and ground rules (Moderator; 5 minutes)	
Presentations to Set the Stage (11:05–11:40 a.m. ET)	
Overview of Existing Abatement Technologies (Michael Bellmann, itap)	15 minutes
Overview of BOEM/NOAA Monitoring & Proposed Target (Samuel Denes, BOEM)	15 minutes
Break	5 minutes
Mural Discussion and Feedback (11:40 a.m.–12:55 p.m. ET)	
Introduction to Mural	5 minutes
Review Results of Pre-Workshop Industry Questionnaire	5 minutes
Discussion Questions **1.** Which **noise abatement technologies** are most promising for **reducing low-frequency noise propagation**? **2.** For **bubble curtains**, what are the **pros, cons, and gaps** in knowledge? **3.** For **other noise abatement technologies**, what are the **pros, cons, and gaps** in knowledge? **4.** What are the **research needs** to advance noise reduction strategies? Please consider the example quieting target presented by BOEM. **5.** What **monitoring data** is needed to understand the efficacy of noise reduction strategies? **6.** What **monitoring technology advances** are needed to understand the efficacy of noise reduction strategies? **7.** What **investments** could be made to overcome remaining barriers? **8.** What do you recommend as **next steps** relating to gaps and recommendations?	65 minutes
Wrap-Up and Acknowledgments (12:55–1:00 p.m. ET)	
Close out Session 2 and discuss next steps (Moderator; 5 minutes)	

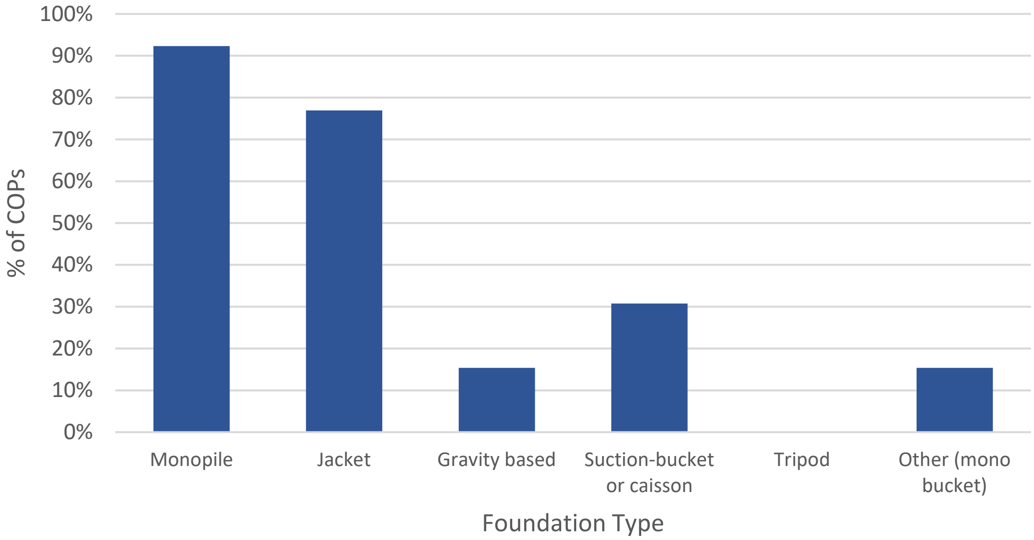
Appendix B: Review of Construction & Operations Plans

The project team reviewed 12 existing offshore wind energy projects' Construction & Operations Plans (COPs) and one Environmental Assessment to gather existing data on noise reduction strategies for the installation of fixed-bottom offshore wind foundations, including the practicality of using alternative foundations and installation methods and the effectiveness of existing noise abatement technologies. The following results were used to inform the workshop.

1. Which **regions** does the fixed-bottom offshore wind work primarily relate to? Select all that apply.



2. Which **foundation types** are being considered for use? Select all that apply.



Note that the percentage on the y-axis totals to >100% because several COPs identified multiple foundation types as potential options.

3. Are any **other innovative foundation types** being considered for noise and substrate vibration mitigation, and if so, which?

- mono bucket, differentiated mono buckets
- suction bucket jackets, suction bucket tetrahedron

4. What are the **primary engineering driving factors** for the choice of foundation types?

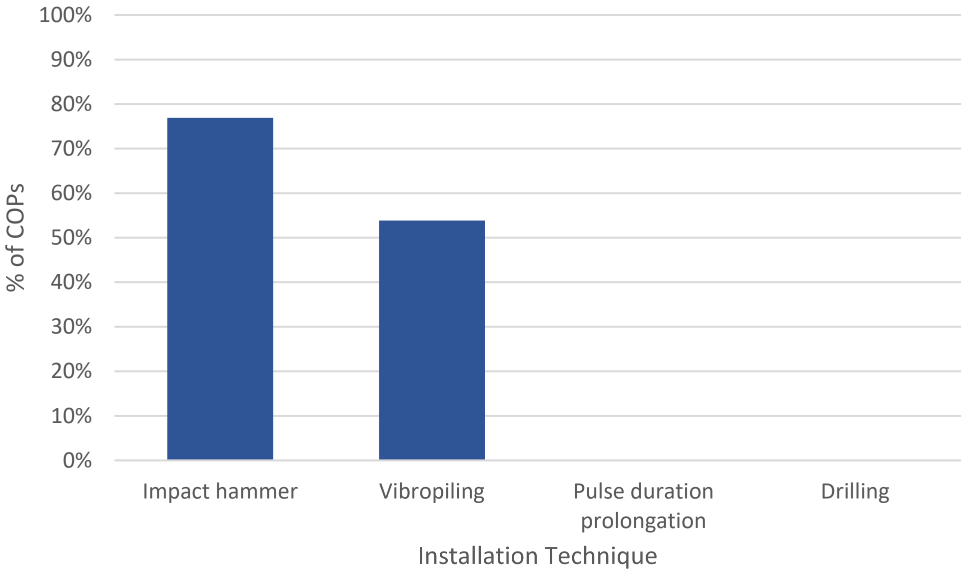
Factors	# of COPs	% of COPs
Seabed characteristics	10	77%
Water depth	10	77%
Other environmental design considerations	2	15%
Rate of installation	0	0%
Layout constraints	0	0%
Other (size of WTC and OCS platform)	4	31%

5. What are the **primary economic driving factors** for the choice of foundation types? Please rank in order of priority.

Factors	# of COPs	% of COPs
Supply chain availability	7	54%
Domestic content (*no distinction in COPs between global and domestic)	7	54%
Global content	0	0%
Production costs	6	46%
Installation constraints	5	38%
Environmental effects considerations	5	38%

6. Which **alternative foundations** are most promising for the choice of foundation types?
   - None specified

7. Which **installation techniques** are being considered for use? Select all that apply.

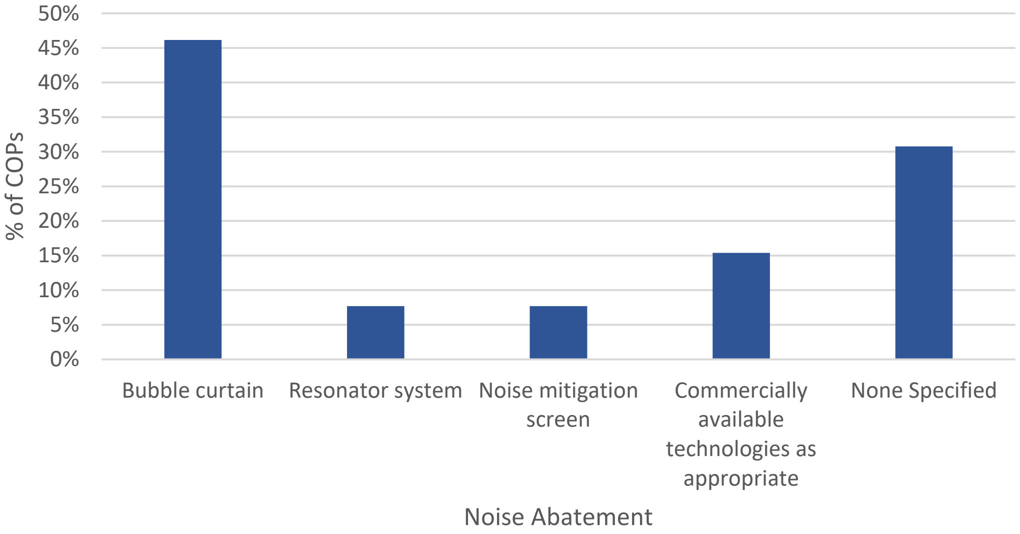


Note that the percentage on the y-axis totals to >100% because several COPs identified multiple installation techniques as potential options.

8. Are any **other alternative installation techniques** being considered for noise and substrate vibration mitigation, and if so, which?
    - None specified

9. Which **alternative installation techniques** are most promising for **reducing low-frequency noise propagation**?
    - None specified

10. Which **noise abatement technologies** are being considered for use? Select all that apply.



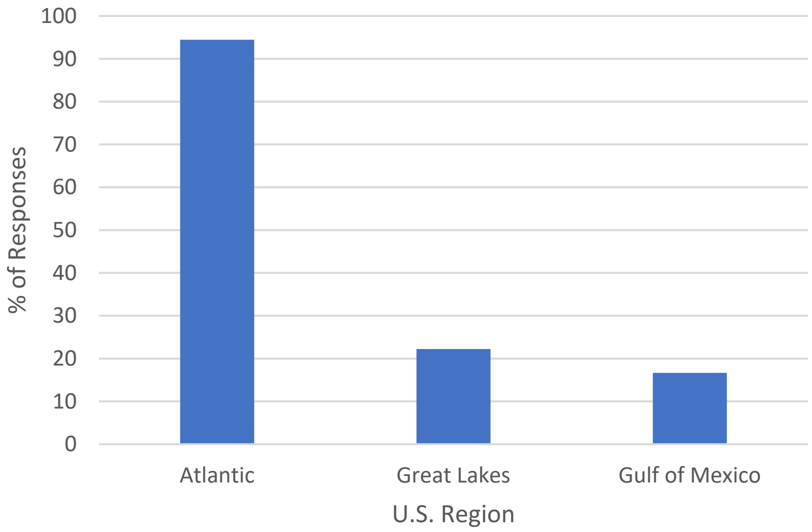
Most COPs identified these noise abatement technologies as examples of what might be used, with the final decision to be made as permitting progresses. No distinction was made between the use of single versus double bubble curtains. Note that the percentage on the y-axis totals to >100% because several COPs identified multiple noise abatement technologies as potential options.

11. Are **other innovative noise abatement technologies** being considered for use, and if so, which?
    - Variability in source levels (x1)
    - Alternative hammer schedules (energies and strikes) (x2)
    - No simultaneous pile driving (x1)
12. What are the **primary driving factors** for the noise abatement technologies that are being chosen? Please rank in order of priority.
    - Effectiveness for species of interest (x1)
    - Applicability to water depths of interest (x0)
    - Level of development and testing (x0)
    - Costs (x0)
13. Which **noise abatement technologies** are most promising for **reducing low-frequency noise propagation**?
    - None specified

Appendix C: Pre-Workshop Industry Questionnaire Results

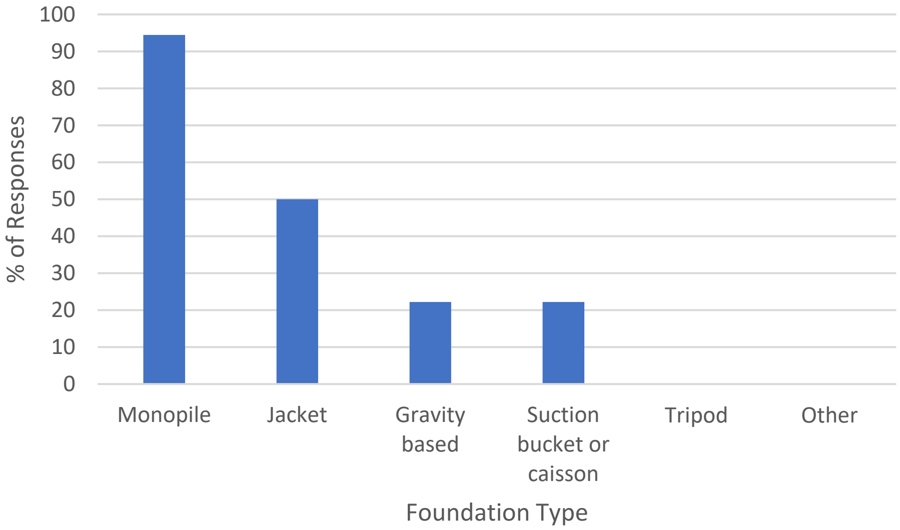
This brief questionnaire aimed to gather feedback from offshore wind energy developers on noise reduction strategies for the installation of fixed-bottom offshore wind foundations, including the practicality of using alternative foundations and installation methods and the effectiveness of existing noise abatement technologies. In total, 18 industry representatives completed the questionnaire. All results were anonymized and used to inform the workshop.

1. Which **regions** does your fixed-bottom offshore wind work primarily relate to? Select all that apply.



Note that the percentage on the y-axis totals to >100% because several respondents identified multiple regions.

2. Which **foundation types** are you considering using? Select all that apply.



Note that the percentage on the y-axis totals to >100% because several respondents identified multiple foundation types being considered.

3. Are you considering any **other innovative foundation types** for noise and substrate vibration mitigation, and if so, which?
    - Nine out of 18 respondents skipped this question.
    - The remaining respondents answered no (x6) or:
        - Floating for the Gulf of Maine
        - No, but we are considering multiple innovative installation techniques.
        - No because the conditions necessitate use of the types of foundations selected. In addition, suction bucket is not commercially viable because it can't be serially produced to the level needed.

4. What are the **primary engineering driving factors** for your choice of foundation types? Please rank in order of priority.
    1. Water depth
    2. Seabed characteristics
    3. Other environmental design considerations (e.g., wind and wave loading)
    4. Rate of installation
    5. Layout constraints
    6. Other (please specific below)

5. If you selected Other, please specify.
    - Supply chain capability
    - Turbine size/loads and permit conditions (noise, seabed area, etc.)
    - Feasibility of building locally
    - Commercial viability/cost

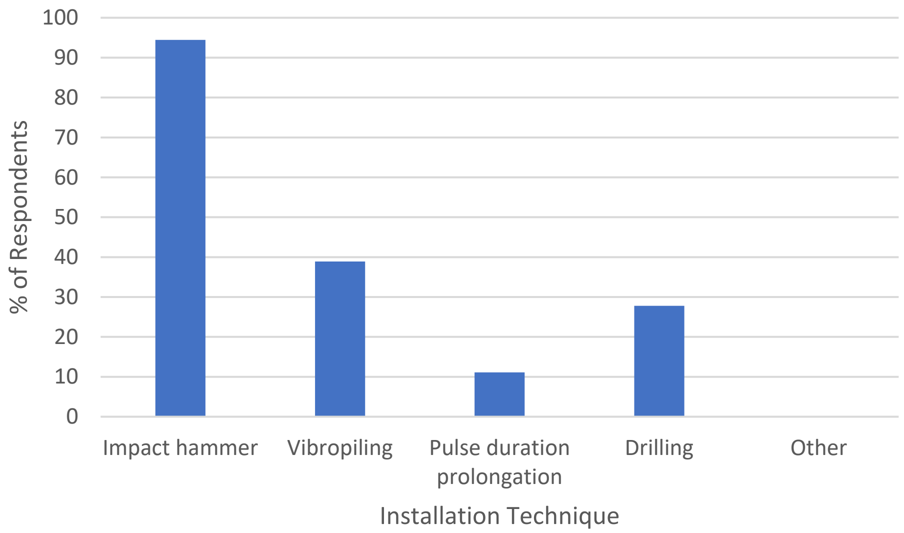
6. What are the **primary economic driving factors** for your choice of foundation types? Please rank in order of priority.
    1. Supply chain availability
    2. Production costs (e.g., fabrication, manufacturing)
    3. Installation costs
    4. Domestic content
    5. Installation constraints (e.g., speed)
    6. Environmental effects considerations (e.g., target species, habitat change, siting)
    7. Global content
    8. Other (please specify below)

7. If you selected Other, please specify.
    - Permit restrictions, including installation constraints
    - Local content, almost regardless of cost

8. Which **alternative foundations** are most promising for **reducing low-frequency (<1 kHz) noise propagation**?
    - Twelve out of 18 respondents skipped this question.
    - The remaining respondents answered:
        - Suction bucket/caisson jackets (x4)

        - Gravity base foundations (x4)

9. Which **installation techniques** are you considering using? Select all that apply.

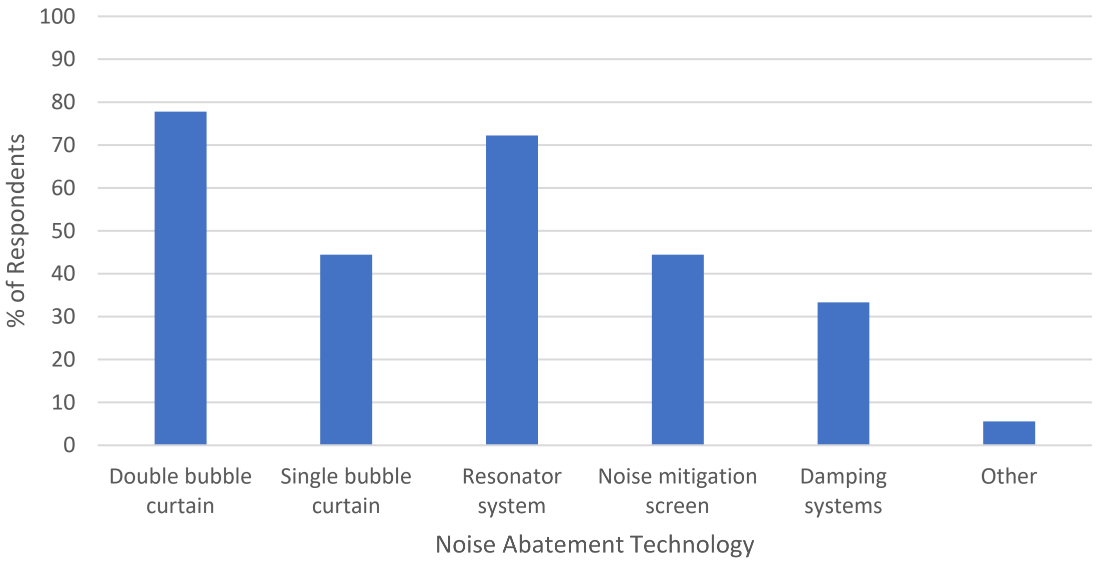


Note that the percentage on the y-axis totals to >100% because several respondents identified multiple foundation types being considered.

10. Are you considering using any **other alternative installation techniques** for noise and substrate vibration mitigation, and if so, which?
    - Fifteen out of 18 respondents skipped this question.
    - The remaining respondents answered no (x2) or:
        - Drilling is for emergency use if a pile gets stuck. Blue piling is not technically ready, but when it becomes available may be leveraged.

11. Which **alternative installation techniques** are most promising for **reducing low-frequency noise propagation**?
    - Thirteen out of 18 respondents skipped this question.
    - The remaining respondents answered:
        - Vibrohammer, pulse technology, hydrohammers, etc.
        - Gravity based, HI/LO piling; Hydrosound damper tuned to low frequency
        - Potentially internal hammer cushions
        - Suction buckets
        - This question is slightly misleading as reduction of low-frequency noise is perhaps not the most important goal to achieve. There are other aspects of sound that should be a greater focus than the frequency band. For example, non-impulsive installation techniques may be more desirable even though they fall within the same frequency as impulsive sounds.

12. Which **noise abatement technologies** are you considering using? Select all that apply.



Resonator systems here included technologies such as the hydrosound damper and AdBm systems. Noise mitigation screens were defined in the questionnaire as any physical barrier external to the pile, and damping systems were defined as a system on the pile itself. The "other" response here was detailed by the respondent as "other near-field attenuation systems" (x1). Note that the percentage on the y-axis totals to >100% because several respondents identified multiple noise abatement technologies.

13. Are you considering using any **other innovative noise abatement technologies**, and if so, which?
    - Eleven out of 18 respondents skipped this question.
    - The remaining respondents answered no or:
        - Adbm (x3)
        - Limit hammer energy
        - Note that the noise mitigation screen is no longer big enough for larger piles., and too heavy to maneuver; not likely a viable option in the future

14. What are the **primary driving factors** for the noise abatement technologies that you are choosing? Please rank in order of priority.
    1. Effectiveness for species of interest
    2. Applicability to water depths of interest
    3. Level of development and testing
    4. Costs
    5. Other (please specify below)

15. If you selected Other, please specify.
    - All 18 respondents skipped this question.

16. Which **noise abatement technologies** are most promising for **reducing low-frequency noise propagation**?
    - Eleven out of 18 respondents skipped this question
    - The remaining respondents answered:
        - Adbm (x2)

- Near-field noise abatement systems and built-in systems
- Near field attenuation systems
- Bubble curtains
- Combination of most technologies
- Hydrosound dampers