Turbine Reefs:

Nature-Based Designs for Augmenting Offshore Wind Structures in the United States

Technical Report

November 2021

The Nature Conservancy

INSPIRE ENVIRONMENTAL

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Rampion offshore wind farm, U.K. © Nicholas Doherty/Unsplash

1.0 INTRODUCTION

1.1 Terms / Definitions

Nature-Based Design (NBD), sometimes called Nature-Inclusive Design (NID), refers to purposeful design of structures, inspired by natural elements and features, to optimize habitat value for native species or communities whose natural habitat has been modified, degraded, or reduced (Hermans et al. 2020). Nature-based designs can be integrated in or added to offshore wind infrastructure.

Offshore wind farm components: Offshore wind farms generally consist of several wind turbines installed on foundations, a network of subsea cables that transport the power generated from each turbine (inter-array cables), and a subsea export cable that transports the power to shore. Foundations may be monopile (placed on a single post), jacket type (standing on multiple legs), or gravity based. Monopile and jacket foundations are driven into the seafloor, and cables are generally buried below the seabed unless seabed conditions prevent burial (e.g., when there is hard bottom).

Scour protection: Scour is the removal of sediments around the base of an object due to the interaction of wave- and current-induced flows with a structure and substrate, similar to erosion (Vineyard Wind, LLC 2020, p. 1-12). To prevent scour or erosion around wind turbine foundations and unburied cables, engineers may decide to utilize scour protection (often in the form of a layer of stone). This report discusses scour protection options that may serve the dual purpose of also enhancing habitat for marine species.

1.2 Background

Offshore wind is an abundant renewable energy resource widely utilized in Europe and Asia and is now rapidly being developed in the United States. With population centers concentrated in coastal areas, U.S. East Coast states have established ambitious targets to source almost 30,000 megawatts (MW) of power from offshore wind by 2035 (ACP 2021).

To meet the goals established by the states, the Department of the Interior's Bureau of Ocean Energy Management (BOEM) created 15 commercial offshore wind lease areas along the U.S. East Coast, with planning underway for additional areas, including off the coasts of New York, South Carolina, California, and Hawaii (ACP 2021). Currently, only two offshore wind farms are in operation in the United States: the 5-turbine, 30-MW Block Island Wind Farm (BIWF) in Rhode Island state waters and the 2-turbine, 12-MW Coastal Virginia Offshore Wind pilot project, located in federal waters, 27 miles (50 kilometers) off the coast of Virginia.

The relatively shallow waters off the U.S. East Coast allow developers access to the offshore wind resource using conventional infrastructure designs. The monopile structure is the most common turbine foundation used in shallow waters, largely due to its simple design, suitability for mass production, and common installation method (pile driving) (Kallehave et al. 2015). Depending on the installation site, monopiles, as well as transmission cables among turbines and to shore, may require protection from scour. Scour results in the erosion of sediments around offshore wind structures and is caused by currents and waves, the presence of mobile sediment types, the restriction and redirection of water flow around the structures, and the development of a horseshoe vortex (Vineyard Wind, LLC 2020, p. 1-12). To limit or prevent the displacement of sediments, scour protection products may be used, such as rocks of specified shapes and sizes placed around the base of the turbine, or in the case of cables, concrete mattresses or rock bags placed on top of portions of exposed cable (Esteban et al. 2019).

Scour protection is usually designed by the engineering team based on modeled shear stress at the base of the foundations. A general approach is to clear the location of rocks and lay a base of gravel, pile-drive the monopile through the gravel, and then place a layer of rocks around the base (Esteban et al. 2019) (Figure 1). The requirements for scour protection vary between lattice jacket structures, monopiles, and gravity-based foundations but can be a substantial footprint for each project.

Offshore wind structures, including the turbines and the scour protection layers at the base of the turbines and along the cable route, may create an artificial reef effect, particularly in areas of soft-bottom habitat (Dannheim et al. 2020). The turbine structures provide new areas for epifaunal organisms to attach and grow; these organisms may be important food sources for upper trophic levels. Scour protection offers new microhabitats and feeding opportunities for a variety of species (DeGraer et al. 2020). However, these installed structures may not function similarly to the natural habitat that is displaced (Strain et al. 2018), and the fauna that colonizes them is often distinctly different from surrounding natural reef or hard-bottom areas (Coolen et al. 2020). A recent review of the artificial reef effect of offshore wind farms identified several modifications to scour protection that could enhance organismal abundance and biodiversity around turbine structures (Glarou et al. 2020). There is an opportunity to utilize knowledge gleaned from previous wind farms and intentional artificial reef

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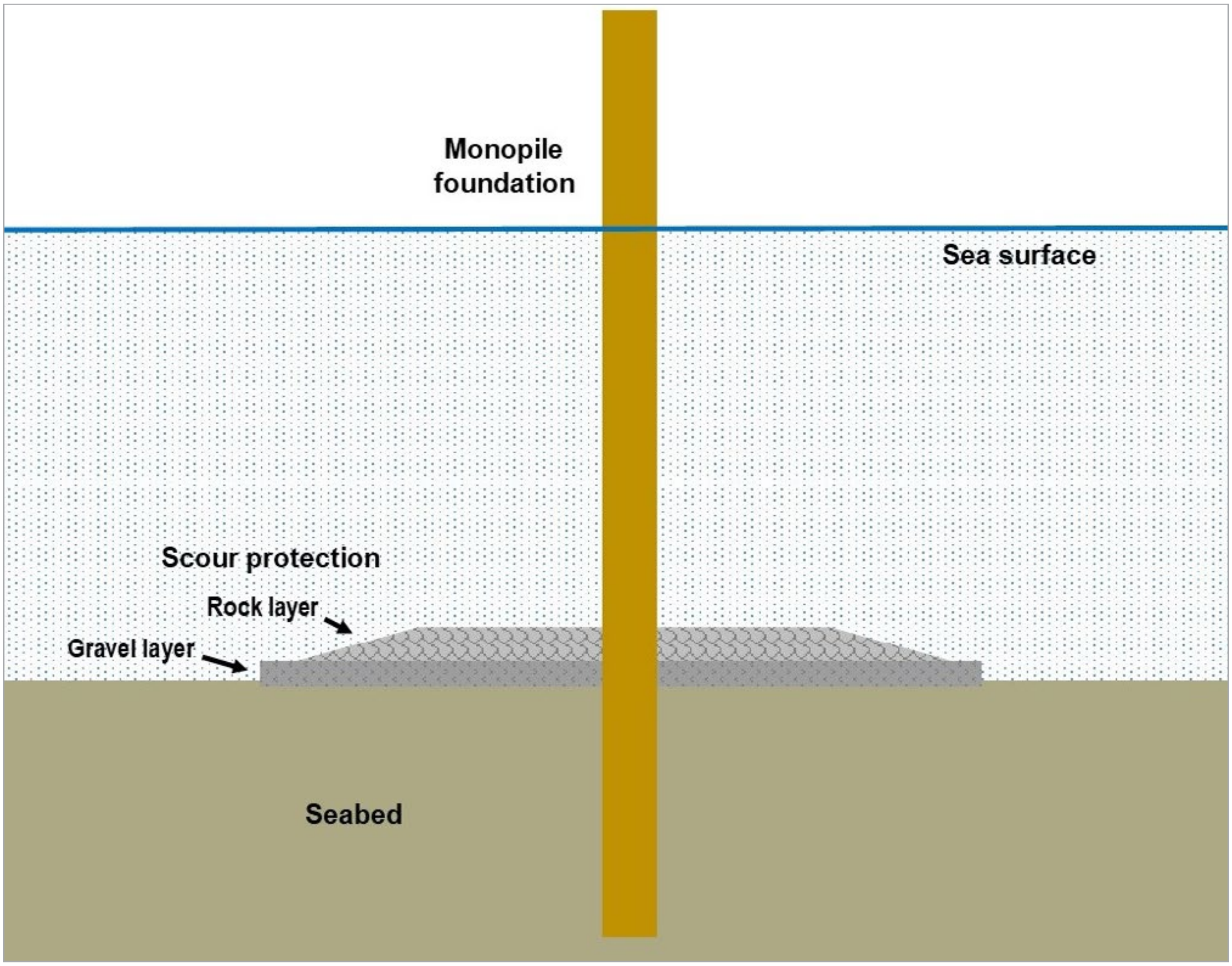

Figure 1. Illustration of common scour protection design (modified from Whitehouse et al. 2011)

restoration projects to design the offshore wind infrastructure to optimize benthic habitat conditions for native species (or communities) whose natural habitat has been modified, degraded, or reduced (Hermans et al. 2020). New structure that is added to lower-value habitat could be designed to optimize habitat value.

Designing offshore wind structures to mimic natural habitat features of the region will facilitate colonization and use by local species and is often referred to as Nature-Based Design (NBD). NBD structures are artificial constructions that serve both economic and ecological purposes (Lengkeek et al. 2017) and can be integrated in or added to the design of offshore wind infrastructure (Hermans et al. 2020).

Utilizing NBD structures in offshore wind project designs to meet engineering requirements, while also enhancing marine ecosystem services, is a relatively new concept. This method has been employed previously in designing coastal defense structures (Firth et al. 2014). For example, coastal areas in Brooklyn, New York, have been enhanced using ECOncrete products to stabilize the shoreline, protect a new beach waterfront, and increase habitat quality compared with standard riprap (Perkol-Finkel and Sella 2015). Similarly, Reef Balls® have been shown to act as a breakwater while simultaneously creating a living shoreline (McFarlane 2017). The Ministry of Agriculture, Nature and Food Quality in the Netherlands aimed to stimulate enhancement of ecological functioning during the development of offshore wind projects in the North Sea by including nature regulations in wind farm site decisions and related permitting (Hermans et al. 2020). Permit holders must make demonstrable efforts to design and build wind farms that actively enhance the ecosystem (Netherlands Enterprise Agency (RVO) 2019).

In response to this regulation, the Netherlands Ministry of Agriculture, Nature and Food Quality commissioned Witteveen+Bos and Wageningen Marine Research to compile a catalogue of European NBD options that includes recommendations for customizing NBD for the specific objective and location of a given offshore wind project (Hermans et al. 2020).

While there is currently no similar government incentive for implementing NBD in U.S. offshore wind farms, The Nature Conservancy (TNC) and INSPIRE Environmental (INSPIRE) are compiling information on existing NBD options fabricated in the United States to further support the development of the NBD market and supply chain in the United States, while also outlining key knowledge gaps and technical considerations that require attention for NBD to reach its full potential within the offshore wind industry.

1.3 Objective

TNC and INSPIRE created a *Catalog of Nature-Based Designs for Augmenting Offshore Wind Structures in the United States* (Appendix) to support the development of the NBD market and supply chain in the United States in concert with the newly emerging U.S. offshore wind industry. This document, modeled after *Nature-Inclusive Design: A Catalogue for Offshore Wind Infrastructure,* a technical report by Hermans et al. (2020), provides suggestions for how the ecological function of offshore wind structures can be enhanced using NBD measures added to the design of an offshore wind structure. The working catalog focuses on existing domestically-built products associated with NBD that could be adapted for use in the US offshore wind industry. Included is a discussion of considerations when selecting appropriate NBD options in the Northwest Atlantic Ocean from Massachusetts to South Carolina. This compilation of viable NBD options for offshore wind developers is considered a working document and may be updated in the future as the U.S. supply chain evolves.

1.4 Identification of Knowledge Gaps

Due to the current limited use of NBD in offshore wind design and construction, informational gaps exist regarding documented benefits to marine environments where NBD has been implemented around offshore wind infrastructure. The anticipated benefits of NBD for various fish and invertebrate species have been estimated by examining Essential Fish Habitat (EFH) designations of various life stages or documenting the distributional overlap of known hard bottom habitats with the areas designated for development by the offshore wind industry.

The majority of artificial reef projects have occurred in areas of barren substrate or previously degraded habitat, and little information exists on increasing complex habitat in areas already deemed complex. Some offshore wind lease areas are positioned either within or adjacent to large natural reef systems, such as Cox Ledge within Rhode Island Sound. Offshore wind infrastructure and NBD products have the potential to act as artificial reefs and extend the footprint of, or enhance, the connectivity between natural reef systems.

Additionally, the majority of artificial reef projects have focused on restoring degraded inshore areas and minimal work has been conducted in offshore

Red hake or ling on Shinnecock Reef in Southampton, NY
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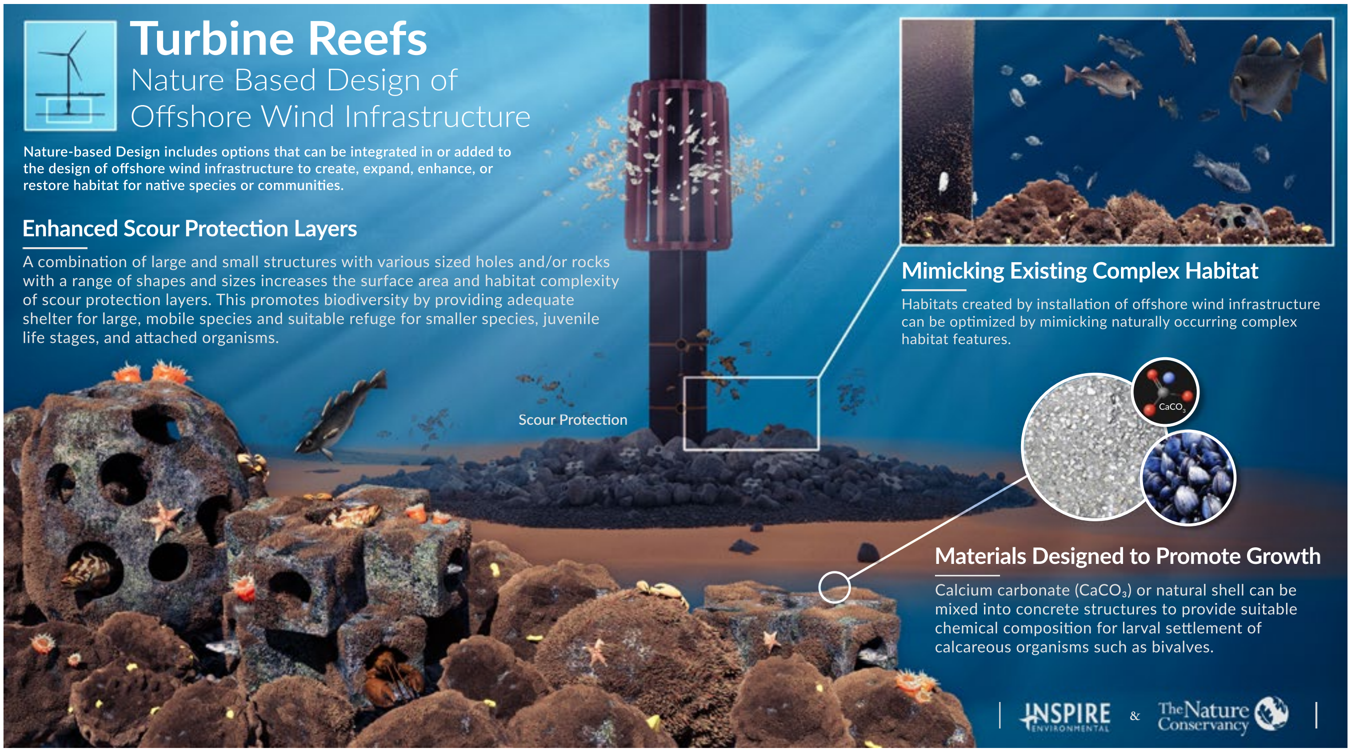

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habitats (Hancock et al. 2021). Increased proximity to hard substrata provides a greater likelihood of larvae and juveniles from surrounding areas arriving and colonizing these structures (Glarou et al. 2020; Petersen and Malm 2006), while also attracting adults that are not produced on-site (Gates et al. 2019). Therefore, potential for settlement and attraction opportunities may be enhanced through the addition of NBD to offshore wind infrastructure.

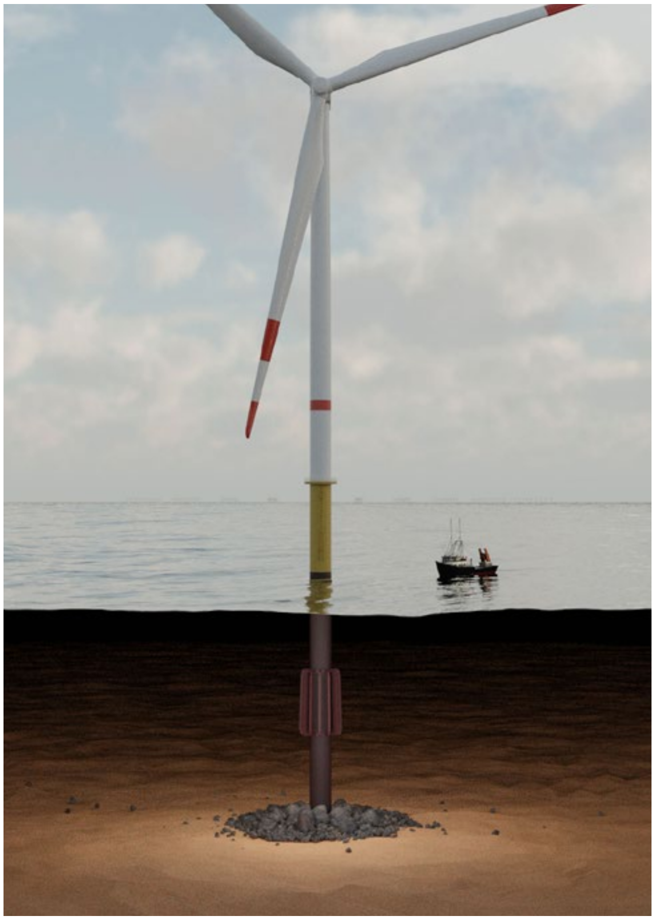
In addition to documenting the ecological benefits of NBD options, there are fundamental engineering knowledge gaps to be addressed. The first step is to demonstrate that adding NBD products will not interfere with the function of traditional scour protection or damage the turbines or cables (e.g., they will not be moved by current or wave activity). The next level of development is to integrate NBD into scour protection itself. This will involve engineering considerations, including sedimentation modeling and dynamic flow modeling, and ultimately mesoscale testing of design options in flume environments. Changes in flow dynamics and the resulting changes in sedimentation due to the placement of objects in the environment must be carefully investigated to maintain the integrity of the offshore wind infrastructure.

1.5 Considerations for NBD Selection

The first step in selecting appropriate NBD options is to identify specific goals for the NBD within the offshore wind infrastructure. Developers should establish measurable objectives they are aiming to achieve by incorporating NBD into their project design. These objectives should align with any specific permitting requirements or mitigation measures and should consider various environmental and engineering factors specific to the project, as discussed below. A monitoring program should then be developed to assess the level of performance of the NBD in meeting the established goals.

1.5.1 Technical Considerations

The specific type of offshore wind structure to be augmented with NBD products should be identified as early as possible in the design phase of project development. Logistically feasible NBD options differ for scour protection layers and cable mattresses,



Monopile turbine with scour protection © INSPIRE Environmental

the primary roles of which are to prevent sediment transport at the base of the turbine foundations and along portions of exposed cable or where only shallow cable burial depths were achieved. Incorporating NBD options should not alter or interfere with the primary scour protection function of these structures. The shape, size, and material of the NBD may be constrained based on whether it will be associated with scour protection at the base of the turbine foundation or along the cable route.

Structure stability, durability, and chemical composition are specific design factors of NBD products that influence the community of sessile epifauna that colonize and establish on the structure (Lengkeek et al. 2017). Slow-growing species such as sponges and corals will only colonize if a substrate is physically stable, while NBD options that are lightweight and easily moved by currents will attract a subset of fast-growing opportunistic epifaunal species that are adapted to frequent physical disturbance. In addition, mimicking natural substrates by mixing calcium carbonate ($CaCO_3$) or natural shell into concrete structures provides suitable chemical composition for larval settlement of calcareous organisms such as bivalves (Lengkeek et al. 2017).

Local environmental physical factors, including depth, current direction, current velocity, and sediment transport, will likely influence the function and performance of NBD structures. These physical factors can alter the epifaunal community that colonizes the NBD structure, and subsequently influence its habitat quality for mobile species like fish and invertebrates. For example, current direction and velocity influence the distribution of hydroid turf in the Northeast Atlantic; one study noted that a hydroid colony provided 3-D microstructure habitat and supported increased biodiversity of mobile fauna (Gates et al. 2019). Under high sediment transport conditions, particular NBD hard-substrate options may trap resuspended sediment; sediment accumulation in NBD structure crevices may negate the value of these spatial niches as shelter for mobile fauna and attachment sites for epifauna. Current speeds are generally stronger nearest the monopile and weakest around the outer edges (Lengkeek et al. 2017). A tradeoff exists between placing NBD options around the outer edges of scour protection where sedimentation rates are higher, or closer to the monopile where current speeds are higher and lightweight products could potentially be moved.

1.5.2 Logistical Considerations

The co-existence of other anthropogenic activities in the vicinity of the wind farm, such as commercial and recreational fisheries, should be considered when determining feasible NBD options. For example, placement of NBD structures is generally not suitable in areas where mobile, bottom-tending fishing gear such as trawls and dredges are used, or where there are other exposed fishing gear types, such as pots and gillnets (Kirkpatrick et al. 2017). In general, the use of NBD options should be limited to areas that will not create additional conflicts with the commercial fishing industry.

Any NBD structure included in the wind project's design may only be in place for the length of the project's operational life (approximately 20–30 years), unless changes or exemptions to current U.S. regulations are made as informed by scientific monitoring documenting the ecological value of these novel habitats. Currently, regulations require all artificial structures be removed at the end of a project's operational life, to a depth of 15 feet (4.6 meters) below the mudline (BOEM: 30 CFR § 585.910a). However, a recent review on the impacts of decommissioning artificial structures provides the case for considering alternatives to this regulation. The paper emphasizes the potential importance of artificial submerged structures as complex habitats that can support a rich localized food web long after the project's lifespan (Fortune and Paterson 2020). This ecological importance can only be quantified through careful habitat monitoring of these novel hard surfaces, including the NBD products, throughout the operational life of the project. Documenting the established epifaunal community inhabiting the project structures, including the NBD products, will provide information on the habitat value, including its value as a refuge and food source for fish and invertebrates. The data gathered from these post-construction surveys should be used to inform decommissioning strategies, as well as inform the design and development of NBD options in the future.

The Rigs-to-Reef program is a functional example of artificial structures being left in situ to continue providing complex habitat for marine life. Upon decommissioning of oil and gas platforms in the Gulf of Mexico and California, developers apply to leave a portion of each structure in place to continue functioning as an artificial reef (Fortune and Paterson 2020); California guidelines even call for enhancement of artificial habitat upon decommissioning (Schroeder and Love 2004). Part of the costs saved by not removing the entire structure are put toward management of the artificial reef (Fortune and Paterson 2020). Monitoring studies that have been sponsored by the federal government include addressing habitat value, fish recruitment and attraction, and impacts to species upon platform removal (BSEE 2021).

Atlantic cod under a shipwreck © NOAA Fisheries

1.5.3 Ecological Considerations

Generally, NBD products aim to provide structure and, upon colonization by basal trophic levels, food resources for a variety of higher trophic level species, including fish and mobile invertebrates. Within that context, the specific ecological goals of the NBD for each project, such as the species or group of species expected to benefit, should be considered when selecting an appropriate design or approach. These ecological goals should be established within the context of site-specific technical and logistical considerations, as described above. NBD options should be selected to enhance the species or group of species of interest, which may include commercially valuable species and/or ecologically important species.

The specific design elements of the NBD product coupled with ecological and environmental conditions will generally influence the types of organisms that utilize it as habitat. For example, using larger structures will provide adequate shelter and crevices for larger, mobile species. Conversely, including smaller structures in the design will offer more suitable refuge for smaller species, juvenile life stages, and epifaunal organisms that utilize substrate for attachment. The textured surface of scour protection allows colonization by sessile organisms and has been shown to provide Atlantic cod and pouting with adequate energy to grow and reproduce (De Troch et al. 2013). The combination of various sized holes on an engineered substrate (or the use of a range of rock sizes) increases surface area and habitat complexity and subsequently can enhance biodiversity (Lengkeek et al. 2017). The number and size of holes present in NBD options can influence the species and life stages that are likely to use the new shelter. Adult American lobster (*Homarus americanus*) select crevices similar to their body size (Cobb 1971) and incorporating a suite of hole sizes will attract a range of lobster size-classes (Barry and Wickins 1992).

Non-mobile epifauna use structure for attachment purposes and can prefer areas of higher current velocities. An example of this is provided by Gates et al. (2019), who demonstrated that hydroid turf increased biodiversity by supporting new microhabitat for amphipods and polynoids, offering prey for asteroids, and supporting food sources for fish observed on-site (Gates et al. 2019). In the United States, habitat provision by attached epifauna may be facilitated by species such as the blue mussel (*Mytilus edulis*), and scour protection can host assemblages similar to natural rocky reefs (Coolen et al. 2018). This was apparent at the BIWF, where the area beneath the turbine jacket foundations transitioned to dense mussel aggregations in years following installation and provided forage opportunity for crabs (HDR 2020). Blue mussels are also ecosystem engineers; the substrate provided by the species allows for increased attachment and shelter opportunity, which has been found to enhance biodiversity (Norling 2009). Zabin et al. (2010) suggest that Reef Ball® artificial reefs are colonized by mussels and other fouling organisms that have high value as fish habitat. Habitat provision may also occur as a result of colonization by a range of species or communities, including sponges, anemones, hydroids, stone corals, soft corals, sea whips, and tube-forming amphipods and polychaetes, which in turn facilitates communities of motile invertebrates and fish (Steimle and Zetlin 2000).

Fish community structure at artificial reef sites is likely a function of natural populations, so this should be

Frilled sea anemones on Shinnecock Artificial Reef, Hamptons Bay, NY © Fish Guy Photos considered when selecting NBD options. Finfish, such as black sea bass, scup, bluefish, and spiny dogfish, were observed at artificial reefs in Nantucket Sound, off the East Coast of the United States, where species richness was similar to natural reefs (Harrison and Rousseau 2020). In the United States, installed ECOncrete® products served as suitable macrofaunal habitat and attracted various organisms such as algae, invertebrates, post-larval finfish, and mating blue crab (*Callinectes sapidus*) (Perkol-Finkel and Sella 2015).

1.5.4 Risks

There are some risks associated with employing NBD options for mitigation or protective uses. Hermans et al. (2020) recommends considering risk early in the design phase, along with monitoring of installed structures during operational phases, to reduce the potential of negative impacts.

The main technical risks associated with utilizing NBD options include:

1. structural failure of the primary structure,
2. structural failure of the NBD components,
3. design failure during the installation phase, and
4. unforeseen costs.

The main ecological risks include:

1. lack of ecological success,
2. settlement of non-indigenous species,
3. competition between target species,
4. the absence of target species, and
5. food limitation of target species.

See Sections 5.2.1 and 5.2.2 in Hermans et al. (2020) for detailed descriptions of each risk type as described during expert consultations (see Table 5.2 therein which presents the relative likelihood of each risk occurring).

Coastal Virginia Offshore Wind pilot project turbines
© Susan Bates

Atlantic cod © iStock

2.0 METHODOLOGY

A catalog was compiled of NBD products that are currently available from U.S. suppliers and have potential relevance to offshore wind designs. The catalog development began with a review of recent literature that identified the types and characteristics of products that have previously demonstrated NBD benefits (Appendix). The literature review focused on examples and assessments of NBD, NBDs used in offshore environments and, if available, recommendations for employing NBDs around offshore wind structures to maximize functional habitat. Information obtained from the literature review was then used to identify and contact U.S. suppliers of these types of products. A project briefing and questionnaire were sent to each supplier, containing questions about available product designs, known ecological advantages, intended use, and estimated costs. Follow-up correspondence with U.S. suppliers requested additional clarification on their products. Information for each product was then compiled.

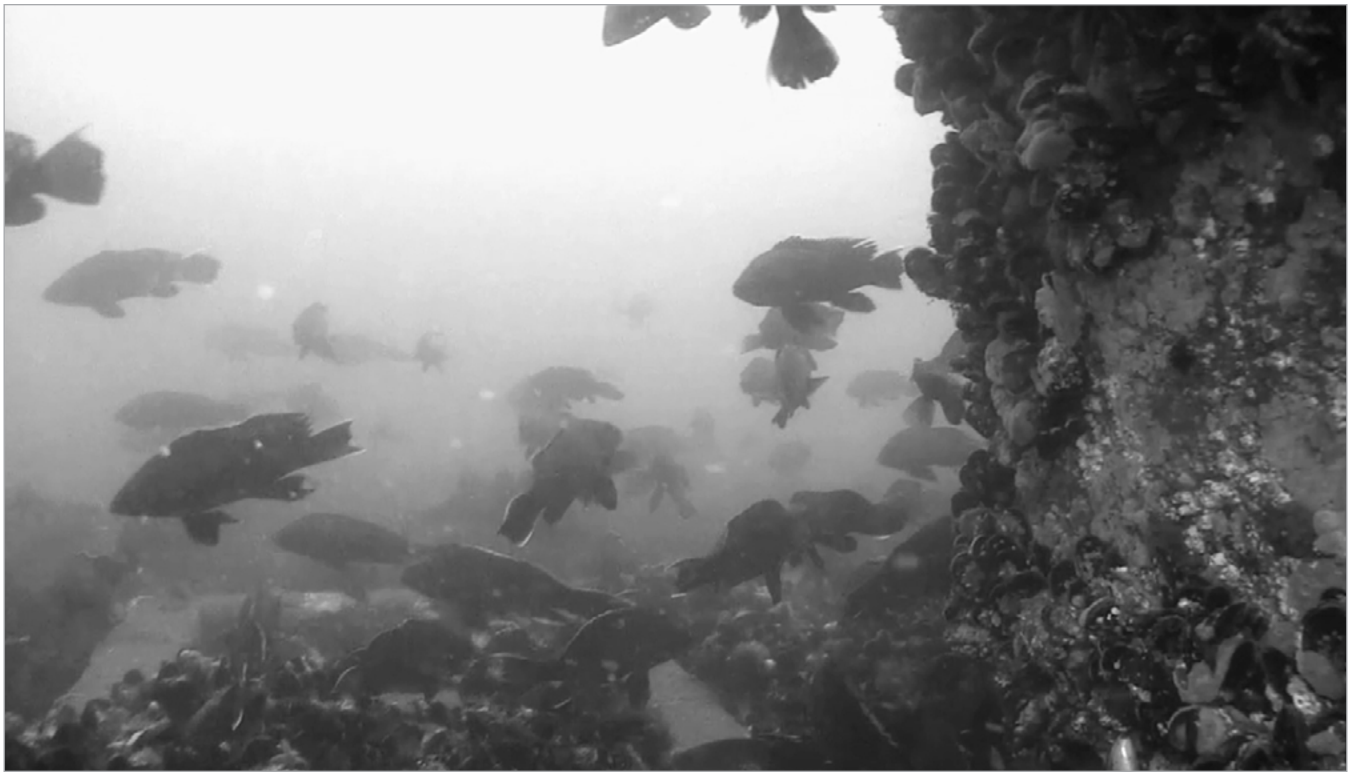
2.1 Focal Species

Offshore wind farms offer the potential to serve as novel habitat to a variety of marine species, including many finfishes, mobile crustaceans, and benthic epifauna (Coolen et al. 2019, Hermans et al. 2020, Vivier et al. 2021). The physical structure of this previously non-existent habitat may provide refuge for mobile species and stable hard substrate for epifaunal species attachment. In turn, established epifaunal communities growing on the offshore wind structures may serve as important food resources for higher trophic levels, including finfish and crustaceans.

The primary value and utilization of new, hard substrate associated with offshore wind farms will likely vary across species groups and life stages. For example, finfish are anticipated to use offshore wind structures mainly during juvenile and adult stages for purposes such as hiding from predators, foraging, juvenile nursery ground, or shelter. But some finfish species, such as ocean pout and Atlantic herring, utilize stable structure for deposition of their eggs

(Stevenson and Scott 2005). Both juvenile and adult American lobster and Jonah crab are expected to utilize offshore wind structures for shelter and hiding purposes. Epifaunal species such as blue mussel, anemones, corals, sponges, and sea whips may colonize the structures as juveniles and adults, creating biogenic habitat (food and refuge) for finfish and crustacean species.

By employing NBD products within the design of offshore wind farms, the value of the novel structure as habitat (both refuge and food resources) may be enhanced for particular species and life stages. Species that associate with complex habitats may colonize turbine structures in areas where complex habitat was absent prior to construction (HDR 2020). This habitat enhancement will be dependent on the specific characteristics of the NBD used and the ecological preferences of local species. Select species and life stages that could benefit from NBD options were identified (Table 1), along with the primary functions of hard substrate for each species. Further information on structured habitat use by focal mobile species (finfish and crustaceans) is outlined in Table 2. The species that were included in the list met one or more of the following criteria: (1) species with existing Essential Fish Habitat (EFH) within the current wind leases along the U.S. northeast coast; (2) species without an official EFH designation, but with habitat preferences and geographic range that overlap with current wind leases along the U.S. northeast coast; (3) species considered to have high economic (commercial or recreational) or ecological importance in the region; and (4) species that may be considered sensitive to impacts from offshore wind development. Species found at the BIWF were also considered to be regional examples of sessile and mobile marine life that may colonize NBD structures in offshore southern New England (HDR 2020). The species included in this report are by no means an exhaustive list, but rather species that may be representative of a larger group that exhibit similar habitat and ecological preferences.



Black sea bass at Block Island Wind Farm © Hutchison

Table 1. Focal Species with Potential to Utilize NBD Options Around Offshore Wind Structures

Common Name	Scientific Name	Life Stage Associated with Structured Habitat	Primary Function of Hard Substrate
Finfish			
Atlantic Cod	*Gadus morhua*	J, A	N / F / S / R
Atlantic Herring	*Clupea harengus*	E	A
Black Sea Bass	*Centropristis striata*	J, A	N / F / S
Gag Grouper	*Mycteroperca microlepis*	J, A	F/ S / N / R
Gray Triggerfish	*Balistes capriscus*	E, J, A	F / S / N / R
Haddock	*Melanogrammus aeglefinus*	J, A	N / F / S
Ocean Pout	*Macrozoarces americanus*	E, J, A	N / F / S / R
Red Hake	*Urophycis chuss*	J, A	N / S
Scup	*Stenotomus chrysops*	J, A	N / F / S
Summer Flounder	*Paralichthys dentatus*	J, A	F
Tautog	*Tautoga onitis*	J, A	N / F / S
Crustaceans			
American Lobster	*Homarus americanus*	L, J, A	N / S
Jonah Crab	*Cancer borealis*	J, A	F / S
Rock Crab	*Cancer irroratus*		F / S
Mollusks			
Blue Mussels	*Mytilus edulis*	J, A	A
Eastern Oyster	*Crassostrea virginica*	J, A	A
Anthozoa			
Frilled Anemone	*Metridium senile*	J, A	A
Northern Star Coral	*Astrangia poculata*	J, A	A
Sea Whip	*Leptogorgia virgulata*	J, A	A
Sponges			
Boring Sponge	*Cliona celata*	J, A	A
Red Beard Sponge	*Microciona prolifera*	J, A	A

A – Adult
E – Egg
J – Juvenile
L – Post-larvae

A – Attachment
F – Foraging
N – Nursery
R – Reproduction
S – Shelter

Table 2. Structured Habitat Use by Focal Mobile Species

Species	Life Stages	Association With Structured Habitat
Atlantic Cod	Juveniles	Juvenile cod survival is increased in gravel/cobble habitats (vs. sand) and increases further in the presence of cobble/gravel with attached epifauna (Lindholm et al. 1999). Increased habitat complexity improves juvenile survivorship by assisting with predator avoidance (Lindholm et al. 1999). When predators are present, juvenile cod take refuge in a wide variety of complex substrates and vegetation (Lough 2004).
	Adults	Adults feeding on a rocky bottom along a 100-m depth contour (Lough 2004) favored areas with boulder-size rocks (minimum 256 mm), bounded by smaller-diameter sediments such as gravel, sand, or mud (Lindholm et al. 2007). Spawning habitat may be associated with clam and mussel beds (DeCelles et al. 2017).
Atlantic Herring	Eggs	Herring deposit eggs on a variety of hard/stable substrates in areas with strong currents (Stevenson and Scott 2005). Eggs may be laid on boulders, rocks, shell fragments, gravel, and benthic macrophytes (Stevenson and Scott 2005). Eggs attach to the bottom and may form mats several layers deep (Stevenson and Knowles 1988).
Black Sea Bass	Juveniles	Newly settled utilize shell fragments near reefs as shelter (Drohan et al. 2007). Juvenile recruitment strength for black sea bass may be strongly affected by the availability of shelters that serve as predation refuges (Drohan et al. 2007).
	Adults	Black sea bass are a strongly structurally oriented fish and frequently inhabit structurally complex bottoms such as natural and artificial reefs, boulder fields, coral patches and other biogenic structures, and shellfish beds (Drohan et al. 2007).
Gag Grouper	Juveniles and Adults	Snapper-grouper species are associated with coral reefs, live/hard bottom, submerged aquatic vegetation, artificial reefs, and medium- to high-profile outcroppings on and around the shelf break zone from shore to at least 600 feet. Spawning generally occurs on medium- to high-profile offshore hard-bottom habitat (SAFMC 1998).
Gray Triggerfish	Juveniles and Adults	Gray triggerfish are typically found in hard-bottom areas such as wrecks, rock outcroppings, and coral reefs in waters 80 to 300 feet in depth (NCDMF 2021).
Haddock	Juveniles and Adults	Adult and juvenile haddock are associated with hard sand (particularly smooth patches between rocks), mixed sand and shell, gravelly sand, and gravel (Brodziak 2005).
Ocean Pout	Eggs	Ocean pout eggs are deposited in sheltered nests, including rocky crevices, where they are guarded by their parents (Steimle et al. 1999a).
	Juveniles	Juvenile ocean pout are highly reliant on shelter for predator avoidance and have been found in rocky areas with attached macroalgae and in shells offshore (Auster et al. 1995, Steimle et al. 1999a).
	Adults	Rocky shelter is essential for spawning adults (see also eggs) (Smith 1898). Adults may be found on gravel, in rock crevices, and near hard substrate, such as artificial reefs and wrecks (Steimle et al. 1999a).

Species	Life Stage	Association With Structured Habitat
Red Hake	Juveniles	Juvenile red hake are highly associated with structures and frequently found in benthic depressions and shells. As is the case for juveniles of other species, shelter is essential for juvenile survival and as the juveniles get larger, they are increasingly associated with larger structures (i.e., they shift their association from shells and debris to artificial and natural reefs) (Steiner et al. 1982, Steimle et al. 1999b).
	Adults	Adult red hake are generally associated with soft sediments in the northern portion of their range, but they have been frequently found seasonally on hard-bottom artificial and natural reefs off New York, Delaware, Maryland, and Virginia (Ogren et al. 1968, Eklund 1988).
Scup	Juveniles and Adults	Habitats for older juveniles and adults include soft bottoms, on or near structures including natural and artificial reefs, shellfish beds, and rocky ledges (Eklund 1988, MAFMC 1996).
Summer Flounder	Adults	Adult summer flounder utilize ambush tactics when hunting for prey and tend to stay in patchy sand habitats near vegetated or structured bottom utilizing their camouflage ability to avoid detection (Lascara 1981, Mast 1916, Packer et al. 1999).
Tautog	Juveniles	Tautog settle into shallow vegetated estuarine areas, then move to deeper nearshore areas with eelgrass or structures, such as rocks, jetties, or shipwrecks, as they mature. Most juveniles remain in estuaries year-round, but by spring, some juveniles are associated with structures on the inner shelf (Munroe 2002).
	Adults	Adult tautog are sometimes found feeding on sandy bottom, but generally require structures such as rocky reefs, pilings, jetties, boulders, rubble, or mussel beds. The majority of adult tautog from the northern part of the population make seasonal migrations from the estuary in fall to areas farther offshore with more complex terrain (Munroe 2002).
American Lobster	Post-larvae	Post-larvae utilize a variety of habitat types, including nearshore rocky areas, and show a preference for subtidal cobble beds. Post-larvae settle rapidly into rock/gravel, macroalgal-covered rock, salt-marsh peat, eelgrass, and seaweed substrates (Wahle and Steneck 1991, ASMFC 2020).
	Adults	Coastal populations concentrate in areas where shelter is readily available. Offshore populations are most abundant in the vicinity of submarine canyons and along the continental shelf edge (ASMFC 2020).
Jonah Crab	Adults	Jonah crab utilize rocky and soft sediment habitats. They are primarily found in areas with rocky substrates but may also inhabit silt or clay substrates (ASMFC 2015).
Rock Crab	Adults	Rock crab prefer sandy or mud bottom, but are commonly found on coarse gravel or mixed rocky bottom between 6 and 456 meters (Robichaud et al. 2000, Stehlik et al. 1991).

Block Island Wind Farm © Red Vault Productions

3.0 SUMMARY OF NATURE-BASED DESIGN OPTIONS

Table 3 summarizes the NBD products available through U.S. suppliers identified as part of this project. Products were categorized based on their intended use as (1) scour protection material that would be used in place of traditional scour protection methods at the base of a wind turbine; (2) scour enhancement that would be added onto or adjacent to an existing turbine scour protection layer to promote increased colonization of the newly added habitat; or (3) cable protection layer that would be used when inter-array and export cables cannot be adequately buried (for example, the need to cross an existing cable or hard substrate could make burial impossible). Each vendor provided information on their products' intended use, ecological advantages, specifications, and general estimated production costs.

The products described in this catalog may benefit all or some of the focal species identified in Table 1.

Each of these products has key features that may increase the likelihood of colonization by native benthic organisms when compared with typical scour protection methods and encourage a greater variety of species to utilize these habitats. By promoting colonization by a diverse epifaunal assemblage, these structures offer increased ecological benefits to mobile fish and invertebrates.

The placement of additional rock layers on top of or adjacent to traditional scour protection may enhance the use of this habitat by local species, by increasing surface area and complexity, particularly if a mixture of rock sizes and types is deployed. The voids produced by traditional scour protection create refuge areas for finfish (Lindeboom et al. 2011, Reubens et al. 2011) and serve as nursery grounds for local crustaceans (Krone et al. 2017). Artificial reefs made from natural quarried rock are shown to be a cost-effective means to creating functional habitat for local species (Hylkelma et al. 2020). Given these facts, Hermans et al. (2020) suggest using rock layers as an add-on option to increase the complexity already present in scour protection. Although this report does not outline specific vendors for bulk mined stone products, this could be an additional option for enhancement of a scour layer, and there are many local suppliers of bulk stone material.

In addition, the recycling of decommissioned anthropogenic structures composed of rock material may be a viable source of substrate for this 'add-on' approach. Submerged structures such as derelict piers and bridges composed of artificial materials (e.g., cement), may be an effective source of material. Although the material is artificial, it has been conditioning while submerged within estuarine or marine environments and is likely to be pre-inoculated with microbial biofilms that are important in promoting epifaunal settlement.

Table 3. Summary of Nature-Based Design Options Identified from U.S. Suppliers

NBD Product	Product Use	Supplier	Location
Wind Turbine Scour Protection Unit	Scour material	ECOncrete® USA	NY
Recycled Concrete	Scour material	Janus Materials	SC
Reef Cells	Scour enhancement	Reef Cells	FL
Reef Balls®	Scour enhancement	Reef Innovations, Roman Stone Construction Co.	FL
Layer Cakes®	Scour enhancement	Reef Innovations	FL
Cube Reefs	Scour enhancement	Reef Innovations	FL
ECO Mats®	Cable protection layer	ECOncrete® USA	NY
Fleximats®	Cable protection layer	Roman Stone Construction Co.	NY

Block Island Wind Farm © Red Vault Productions

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Kate Wilke of The Nature Conservancy with a tautog © Captain Monty Hawkins and *Morning Star* crew

Illustration of gravity, monopile, and jacket foundations (from left to right) © INSPIRE Environmental

APPENDIX

Catalog of Nature-Based Designs for Augmenting Offshore Wind Structures in the United States

Offshore wind is an abundant renewable energy resource rapidly being developed in the United States. The relatively shallow waters off the U.S. East Coast allow developers access to the offshore wind resource using conventional infrastructure designs, which generally consist of several wind turbines installed on foundations, a network of subsea cables that transport the power generated from each turbine (inter-array cables), and a subsea export cable that transports the power to shore. Foundations may be monopile (placed on a single post), jacket type (standing on multiple legs), or gravity based. To limit or prevent the displacement of sediments around these hard structures, scour protection may be needed around the base of the turbine or along specific cable sections.

Designing offshore wind scour protection layers to mimic natural habitat features of the region will facilitate colonization and use by local species, often referred to as Nature-Based Design (NBD). NBD constructions are artificial structures that serve both economic and ecological purposes (Lengkeek et al. 2017) and can be integrated in, or added to, the design of offshore wind infrastructure (Hermans et al. 2020).

TNC and INSPIRE Environmental created this *Catalog of Nature-Based Designs for Augmenting Offshore Wind Structures in the United States* and associated technical report to support the development of the NBD market and supply chain in the United States, in concert with the newly emerging U.S. offshore wind industry. The technical report provides suggestions for how the ecological function of offshore wind structures can be enhanced using NBD measures added to the design of these structures. This appendix, modeled after *Nature-Inclusive Design: A Catalogue for Offshore Wind Infrastructure* by Hermans et al.

(2020), contains a working catalog focused on existing domestically built products associated with NBD that could be adapted for use in the U.S. offshore wind industry. This compilation of viable NBD options for offshore wind developers is considered a working catalog and may be updated in the future as the U.S. supply chain evolves. Each supplier provided information on their products' intended use, ecological advantages, specifications, and general estimated production costs.

Products are categorized as follows, based on their intended use:

1. Scour protection material that would be used in place of traditional scour protection methods at the base of a wind turbine.
2. Scour protection enhancement that would be added onto or adjacent to an existing turbine scour protection layer to promote increased colonization of the newly added habitat
3. Cable protection layer that would be used when inter-array and export cables cannot be adequately buried (for example, due to the need to cross an existing cable or hard substrate that prevents burial).

Nature-Based Design Products Included in this Catalog

NBD Product	Product Use	Supplier	Location
Reef Balls®	Scour protection enhancement	Reef Innovations, Roman Stone Construction Co.	FL, NY
Layer Cakes	Scour protection enhancement	Reef Innovations	FL
Cube Reefs	Scour protection enhancement	Reef Innovations	FL
Reef Cells	Scour protection enhancement	Reef Cells	FL
Fleximats®	Cable protection layer	Roman Stone Construction Co.	NY
ECO Mats®	Cable protection layer	ECOncrete® USA	NY
Repurposed concrete	Scour protection material / Scour protection enhancement	Janus Materials	SC
Turbine Scour Protection Unit	Scout protection material	ECOncrete® USA	NY
Additional stone layer	Scour protection material / Scour protection enhancement	As discussed in the technical report, Hermans et al. (2020) suggests using rock layers as an add-on option to increase the complexity already present in scour protection. Although this report does not outline specific suppliers for bulk mined stone products, they should be included when considering NBD options for enhancement of a scour layer, and there are many Atlantic coast quarries that supply bulk stone material.	

These additional products currently produced in other countries are not included at this time but may be available for production in the United States.

NBD Product	Product Use	Supplier	Location	Website
Reef Cubes®	Scour protection enhancement	ARC Marine	UK	arcmarine.co.uk/
Basalt Bags	Cable protection layer	JägerMare Solutions Gmb	Germany	jaegergroup.com/en/jaeger-maresolutions/
Filter Unit®	Cable protection layer	Sumitomo Deutschland GmbH	Global	sumitomo-filter-unit.com/en/
Marine matt®	Cable protection layer	ARC Marine	UK	arcmarine.co.uk/
3D Printed Units	Scour protection enhancement	3DPARE	Europe	giteco.unican.es/proyectos/3dpare/index.html
Anti-Scour Frond Mattress	Scour protection material	Subsea Protection Systems Ltd.	UK	subseaprotectionsystems.co.uk/

Fluke © Fish Guy Photos

Enhanced Scour Protection Layer

Reef Balls®

Product Description

Reef Balls® can be added on top of, placed next to, or integrated into a scour protection layer. They can be customized to meet specific project needs and designed to attract use by specific focal species. Reef Balls® are designed to withstand movement and damage in storms and can be installed using a variety of methods. Reef Balls® can be outfitted with various add-on options that include base units to add height and surface area.

Super Reef Ball, reefinnovations.com

Ecological Advantages

Products are made from marine grade pH-neutralized concrete resulting in a pH similar to seawater. Reef Balls® can be customized to more closely resemble natural habitats by altering the placement, size, and number of holes in the structure. They are constructed with a rough textured surface to promote colonization of marine epifauna. Internal Juvenile Habitat units can be added to provide shelter for juvenile fish.

Specifications

Size: Individual Reef Ball® units come in a range of sizes 12 to 58 in. high and 12 to 78 in. wide
Footprint: 1.8 to 28.3 ft^2 (varies by product)
Surface area available for colonization: 7.25 to 230 ft^2 (varies by product)
Weight of a single unit: 55-5000 lbs. (varies by product)
Max depth previously deployed: 400+ ft
Estimated life of product: 500 years

Estimated Product Costs

Per unit: $45 to $800
Product to cover 2000 m^2: $334,000 to $460,000
Lead time for production: 5 months

Authorized U.S. Reef Ball® Suppliers:

Reef Innovations (FL), reefinnovations.com
Roman Stone Construction Co. (NY), romanstoneco.com
Designed by: Reef Ball® Foundation, ReefBall.org

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*Additional publications can be found at https://reefballfoundation.org/scientific-papers-and-reference/

Layer Cakes

Layer Cake, reefinnovations.com

Product Description

Layer Cakes are designed to provide increased horizontal surface area for colonization of benthic epifauna (when compared to Reef Balls®). Layer Cakes come in a variety of sizes ranging from the 17 x 9-inch Oyster Layer Cake to the 72 x 60-inch Goliath Layer Cake. They can be added on top of, placed next to, or integrated into a scour protection layer and are installed using a crane. Layer Cakes can be customized to meet specific project needs and designed to attract use by specific focal species by customizing the number, shape, and size of layers.

Ecological Advantages

Layer Cakes are made from marine grade pH-neutralized concrete and are constructed with multiple shelf layers. They are constructed with a rough textured surface to promote colonization of marine epifauna; additional layers increase available surface area for colonization. Various natural materials can be added to increase structural complexity such as rocks and shells.

Specifications

Size: Individual Layer Cake units range from 9 to 60 inches in height and 17 to 72 inches in width.
Footprint: varies by product size
Surface area available for colonization: varies by product size
Weight of a single unit: 42 to 5,200 lbs. (varies by product size)
Max depth previously deployed: 400+ ft
Estimated life of product: 500 years

Estimated Product Costs

Per unit: $65 to $1400
Product to cover 2000 m^2: $501,000 to $700,000
Lead time for production: up to 12 months

Authorized U.S. Layer Cake Supplier

Reef Innovations (FL), reefinnovations.com
Designed by:
Reef Ball® Foundation, ReefBall.org

Publications

See Reef Ball® publications

Enhanced Scour Protection Layer

Cube Reefs

Product Description

Cube Reefs can be added on top of, placed next to, or integrated into a scour protection layer and are lowered to the seafloor using a crane. Concrete cube structures can be placed as a single unit or stacked up to five units high. Each cube structure contains a center hole with a diameter of 10 to 12 inches and 4 horizontal holes with 6-to-8-inch openings. Reef cubes can be combined with Reef Balls® for added structural complexity.

Cube Reefs, reefinnovations.com

Ecological Advantages

Products are made from marine grade pH-neutralized concrete and are constructed with holes on each side of the structure, including one in the center, and can be customized to meet specific project needs and designed to attract use by specific focal species by customizing the size. They are constructed with a rough textured surface to promote colonization of marine epifauna, and the addition of multiple product layers increase available surface area.

Specifications

Size: Individual Cube Reef units range from 9 to 13 inches in height and 22 to 36 inches in width (customizable)
Footprint: 4 ft^2 (varies by product size)
Surface area available for colonization: varies by product size
Weight of a single unit: 100 to 500 lbs.
Max depth previously deployed: 70 ft
Estimated life of product: 500 years

Estimated Product Costs

Per unit: $275
Product to cover 2000 m^2: $356,400
Lead time for production: 5-10 months

Authorized U.S. Cube Reef Supplier

Reef Innovations (FL), reefinnovations.com
Designed by:
Reef Ball® Foundation, ReefBall.org

Publications

See Reef Ball® publications

Enhanced Scour Protection Layer

Reef Cells

Product Description

Reef Cell Modules are designed to mimic natural reefs and provide a large amount of surface area with a plethora of interconnected spaces of various size. Units can be added on top of, placed next to, or integrated into a scour protection layer and are installed using a crane. The base of each module provides ballast weight to increase anchoring stability post-deployment.

Reef Cell Module, reefcells.com

Ecological Advantages

Units contain holes in the module surface that allow for interior exchange of seawater and nutrients, sunlight penetration, and egress by mobile organisms. The surface holes also increase module stability by reducing hydraulic drag and lifting forces. Units include large habitat cells on the outer layer. Smaller inner chambers provide shelter for small and juvenile fish. The modules are built utilizing a pH-neutral concrete mix and the exterior surface of each module is impregnated with 30-50 grit calcium carbonate aggregate, which encourages rapid attachment by calcareous organisms.

Specifications

Size: Individual units range from ~5 to 8 feet in height and are ~7 feet in width
Footprint: 12.5 ft^2
Surface area available for colonization: variable
Weight of a single unit: 2,976 to 6,172 lbs
Max depth previously deployed: 60 ft
Estimated life of product: 50+ years

Estimated Product Costs

Per unit: $2,800
Product to cover 2000 m^2: $1,100,000
Lead time for production: 4 months

Supplier:

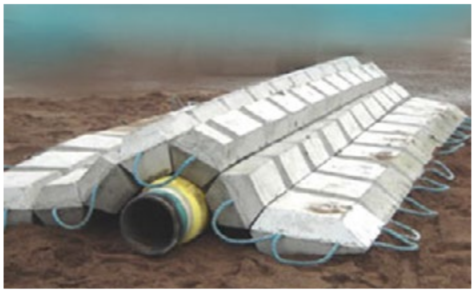
Reef Cells (FL), reefcells.com

Cable Protection Layer

Fleximats®

Product Description

This is a cable protection option that provides a high degree of flexibility, allowing it to closely follow the contours of a pipeline/umbilical cable and seabed. The mat is constructed using high-strength concrete profiled blocks and ultraviolet-stabilized polypropylene rope. Once installed, the Fleximat® may scour into the seabed to increase the stability and be compatible with trawling. Mats can be constructed to meet project-specific size requirements.



Fleximat®, subseaprotectionsystems.com

Fleximat®, romanstoneco.com

Ecological Advantages

Concrete can be made with admixtures that reduce the pH of the concrete and can be textured (see image) to encourage faster colonization of benthic epifauna.

Specifications

Size: 20 x 8 x 1 ft
Footprint: 160 ft^2
Surface area available for colonization: 320+ ft^2
Weight of a single unit: 18,298.4 lbs.
Max depth previously deployed: ~6,500 ft
Estimated life of product: 50+ years

Estimated Product Costs

Per unit: $800 to $1,200
Product to cover 2000 m^2: N/A
Lead time for production: 6 to 9 months

Supplier(s)

Roman Stone Construction Co. (NY), romanstoneco.com
(under license from Subsea Protection Services)

Publications

International Marine Contractors Association (IMCA). 2011. Guidelines for Diver and ROV Based Concrete Mattress Handling, Deployment, Installation, Repositioning and Decommissioning. IMCA D042 Rev 1 / IMCA R016.

Cable Protection Layer

ECOncrete® ECO Mats

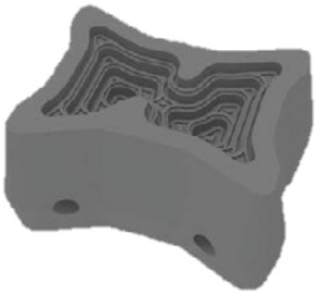
Product Description

These articulated concrete mattresses are designed to provide flexible, stable protection for offshore cables while promoting colonization and use by benthic organisms. Mattresses are composed of interlocking concrete blocks connected with a polyester cable. The concrete mix design includes ECOncrete® Admix and is coupled with complex surface textures to encourage colonization and attachment by marine epifauna. ECO Mat dimensions are tailored and pre-assembled to fit project needs and can be lowered into place by crane and standard lifting equipment.

ECOncrete® ECO Mat, www.econcretetech.com

Ecological Advantages

ECOncrete® units have been shown to enhance growth of ecosystem engineering species such as oysters, serpulid worms, bryozoans, and coralline algae, compared with Portland cement units. These species (oysters, serpulid worms, barnacles, and corals) deposit their $CaCO_3$ skeletons onto hard surfaces, thus creating valuable habitat for other benthic organisms as well as generating an active carbon sink over the lifespan of the structure.



ECOncrete® ECO Mat block

Specifications

Size/Footprint/Surface area for Colonization: according to project requirements
Weight of a single unit: variable
Max depth previously deployed: 20 ft.
Estimated life of product: 30+ years

Estimated Product Costs

Per unit: \$12 to \$18 per ft^2
Product to cover 2000 m^2: N/A
Lead time for production: 3 months

Supplier(s)

ECOncrete, econcretetech.com

Publications

Perkol-Finkel, S., and I. Sella. 2014. Ecologically active concrete for coastal and marine infrastructure: innovative matrices and designs. In: Allsop, W., Burgess, K. (Eds.), From *Sea to Shore — Meeting the Challenges of the Sea*. ICE Publishing, pp. 1139–1149.

Perkol-Finkel, S., and I. Sella. 2015. Harnessing urban coastal infrastructure for ecological enhancement. *Maritime Engineering*, 168 (MA3): 102–110.

Sella, I., and S. Perkol-Finkel. 2015. Blue is the new green — Ecological enhancement of concrete based coastal and marine infrastructure. *Ecological Engineering*, 84: 260–272. ISSN 0925-8574.

Sella, I., T. Hadary, A. Rella, B. Riegl, D. Swack, and S. Perkol-Finkel. 2021. Design, production, and validation of the biological and structural performance of an ecologically engineered concrete block mattress: A Nature-Inclusive Design for shoreline and offshore construction. *Integr. Environ. Assess. Manag.,* 2021;00: 1–15.

Scour Protection Material / Enhanced Scour Protection Layer

Repurposed Concrete

Product Description

Concrete and steel are highly durable and stable materials. Utilizing aggregate materials that have already been manufactured and submerged in seawater as a result of heavy civil engineering works (e.g., bridges) as they are being decommissioned may be cost effective compared with using newly manufactured products. Materials could be utilized as scour or as add-on units to increase habitat complexity of existing scour products. Material would be gravity fed from a barge for installation.

Recycled aggregate, Janusmaterials.com

Ecological Advantages

Concrete or rock material that has already been submerged in a marine environment has properties that allow for quicker colonization of marine epifauna. Concrete from bridges has demonstrated a high success rate as artificial reef material in marine and estuarine environments. Sequestered CO_2 mitigates the emission of CO_2 from newly manufactured materials.

Specifications

Size: ranges from pea gravel or 57 stone to large riprap and large structured pieces
Footprint: N/A
Surface area available for colonization: variable
Weight of a single unit: ~150 lbs per cubic foot
Max depth previously deployed: N/A
Estimated life of product: 50 years

Estimated Product Costs

Per unit: $25 per ton
Product to cover 2000 m²: $50,000
Lead time for production: 1 month (can vary based on availability of materials)

Supplier(s)

Janus Materials (SC), janusmaterials.com

Publications

Artificial Reef Subcommittees. 2004. Guidelines for marine artificial reef materials. Atlantic and Gulf States Marine Fisheries Commissions, the United States.

ECOncrete® Wind Turbine Scour Protection Unit

Product Description

ECOncrete® Wind Turbine Scour Protection Units are fully structural, interlocking, ecological concrete units that are gravity fed from a barge, intended to replace/complement rock armor scour protection around the base of offshore wind turbines. The ecological design of the units and interstitial spaces between them create an environment that mimics optimal marine habitats, while providing the structural functionality required of armoring for scour protection. These units are still in development and will be piloted for Northeast offshore infrastructure in spring 2022.

Example of an ECOncrete® Wind Turbine Scour Protection Unit © econcretetech.com

Ecological Advantages

ECOncrete® products are composed of bio-enhancing concrete matrices suited for specific environmental and structural needs and are coupled with unit designs and surface textures that mimic features naturally found in marine environments. This design approach has been shown to result in on-site habitat creation, including an increase in juvenile fish and sessile organisms, a decrease in the dominance of invasive species, and significant improvement in water quality. A layer of calcium carbonate is formed on the concrete that provides an active carbon sink over the lifespan of the structure.

Specifications

Size: Individual units are approximately 1.3 ft. (W) x 2.0 ft. (L) x 0.7 ft. (H) but are designed to be combined to form an interlocking array.
Footprint: Approximately 2.5 ft^2 per individual unit
Surface area available for colonization: Approximately 7.5 ft^2 per individual unit
Weight of a single unit: Approximately 150 lbs.
Max depth previously deployed: N/A
Estimated life of product: 30+ years

Estimated Product Costs

Per unit: $10–13
Product to cover 2000 m^2: $10,000 to $14,000
Lead time for production: ECOncrete® should be contacted at least 3 months in advance when purchasing products.

Supplier(s)

ECOncrete® Inc., www.econcretetech.com

Publications

See ECOncrete® ECO Mat publications

References

Hermans, A., O.G. Bos., and I. Prusina. 2020. (Technical Report). *Nature-Inclusive Design: A Catalogue for Offshore Wind Infrastructure*. Witteveen+Bos. Den Haag.

Lengkeek, W., K. Didderen, M. Teunis, F. Driessen, J.W.P. Coolen, O.G. Bos, S.A. Vergouwen, T. Raaijmakers, M.B. de Vries, and M. van Koningsveld. 2017. Eco-friendly Design of Scour Protection: Potential Enhancement of Ecological Functioning in Offshore Wind Farms: Towards an Implementation Guide and Experimental Set-up. (Report / Bureau Waardenburg; No. 17-001). Bureau Waardenburg. https://edepot.wur.nl/411374

Dev Kalidhasan/Unsplash

nature.org/turbinereefs

The Nature Conservancy

INSPIRE ENVIRONMENTAL

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