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WIND ENERGY SCIENCE
DISCUSSIONS

Optimizing offshore wind export cable routing using GIS-based environmental heat maps

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Abstract. In the United States, there are plans to produce up to 30 GW of offshore wind power by the year 2030, resulting in numerous seabed lease areas which are currently going through the leasing or construction & operations phase. A key challenge associated with offshore wind is optimal routing and installation of the subsea power cables, which transmit power from the main offshore wind energy production area to a land-based station, where it connects to the electrical grid. By traversing a vast extent of the seafloor, the installation and operational phases of subsea power cables have the potential to result in a range of environmental impacts, which may negatively affect sensitive biological, physical and human and/or cultural resource receptors. Presented here is a case study from southeastern North Carolina to identify optimal seabed cable routes and coastal landfalls for a recently leased offshore wind farm by using a combination of publicly available data, coupled with standard environmental impact assessment methodologies and GIS-based heat maps. The study identified a range of high-risk areas, in addition to a number of potential low risk routes and landfall areas which minimize seabed user conflicts and impacts to environmentally sensitive locations. Although additional high resolution and site specific environmental, geological and biological surveys are required to develop a robust cable installation plan, the preliminary steps from this research optimizes early phase marine spatial planning for offshore wind projects and other similar subsea industries.

1.0 Introduction

Offshore wind is predicted to grow exponentially across the United States, with a target of 30GW of power by the year 2030 (Energy, 2021). Off coastal North Carolina, which forms the focus of this study, the state has an ambitious wind energy goal of 2.8 GW of offshore wind energy by the year 2030, which is set by the state's current renewable energy targets and based on Executive Order No. 218 (NC DEQ, 2023). A key challenge associated with offshore wind includes optimal routing and installation of the subsea power (export) cables, which transmit power from the main offshore wind energy area to a land-based station, where they connect to the electrical grid. By traversing a vast extent of the seafloor, the installation, operational and de-commissioning phases of subsea power cables have the potential to result in a range of environmental impacts, which may negatively affect sensitive biological, physical and human and/or cultural resource receptors (OSPAR, 2012; BOEM, 2023a).

Several studies, especially from Europe, have assessed potential effects of export cables on a range of abiotic and biotic marine environments (Worzyk, 2009; Hammar et al, 2014; MMO, 2014; English et al., 2017; Taormina et al., 2018). During the initial export cable installation burial and operational phase, a number of different effects are generated, which include noise, electromagnetic fields (EMF), thermal effects and increases in turbidity. Acoustic disturbances have the potential to alter the behavior of surrounding organisms, but studies have generally shown a low probability of inflicting bodily harm or mortality on nearly all taxa that have been observed (Nedwell et al., 2012; Mooney et al., 2020). During the operational power transmission phase, electromagnetic fields (EMFs), in addition to thermal effects, emitted by the export cable also have the potential to impact marine life (Gill, 2005; Snyder et al., 2019). Taormina et al. (2018) identified EMF effects as being a key knowledge gap in offshore wind development. Initial research has shown that benthic species exhibit mixed responses to EMF in lab settings, though behavior alteration is a consistent outcome (Albert et al., 2020). Cumulative impact assessments have also determined the impacts of EMF to be minor compared to other potential effects associated with subsea power cables (Bergstrom et al., 2014; Copping et al. 2020). Proper cable burial, ideally 1-2 m beneath the seafloor, is known to reduce transmission related EMF effects, in addition to associated thermal effects (Snyder et al, 2019). Where cable burial is not possible due to substrate type, the placement of mattressing, boulders or concrete is a common approach (OSPAR, 2008; BOEM, 2023a).

Direct alteration of the seabed and increased suspended sediments are known physical effects attributed to export cable installation (Taormina et al., 2017). These physical changes have the potential to indirectly affect various organisms in the surrounding ecosystem due to the disturbance (Gill, 2005; English et al, 2017). Suspended sediments generated from jetting, trenching and/or plowing during cable installation is known to degrade water quality and result in increased turbidity, with potential impacts on surrounding benthic and aquatic organisms (Worzyk, 2009; Bergstrom et al., 2014; Methratta et al., 2021). Increased suspended sediment effects are largely localized, as long-term effects are diminished with increasing distance from the altered seabed areas (Methratta, 2021; English et al, 2017; MMO, 2014). Habitat alteration from stabilizing structures placed on the seabed to reduce cable mobility are known to have a generally positive effect on benthic communities as well as fish populations (Taormina et al., 2017; Perry & Heyman, 2020). The positive social impacts associated with offshore wind are evident in the eastern United States, both within recreational fisheries circles and among other ocean users (Voss et al., 2013; Smythe et al., 2021).

In addition to environmental impacts, submarine hazards pose another challenge for managing risks associated with export cables. Monitoring conducted for other OWF sites, predominantly in northern Europe, has revealed some of the potential effects, and possible mitigation practices, for export cable route planning and installation. In a case study that examined dozens of OWF's, cable exposure and free span due to scour or improper burial occurred at some offshore wind locations (English et al., 2017). Research has shown that avoidance of submarine geohazards (e.g. steep seabed areas, earthquake prone locations) is critical for cable route selection and infrastructure protection (Carter et al., 2014). Cumulative impact assessments - to reduce potential impacts attributed to other marine activities - using geospatial techniques, is a common approach in offshore wind impact studies (Carter et al., 2014; Lonsdale et al., 2020; Hammar et al., 2020; Choi et al., 2021; Gusatu et al., 2021).

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The main aim of this study is to explore the environmental impacts associated with subsea power cable installation and transmission, and to propose monitoring and mitigation techniques to guide optimal subsea power cable routing. This will be accomplished using an innovative combination of desktop studies of publicly available data, coupled with standard Environmental Impact Assessment (EIA) methodologies and GIS-based geospatial and modelling methods. The ultimate aim is to optimize marine spatial planning, minimize ecological impacts and assist with critical coastal and offshore management decision-making during the early phases of offshore wind farm development.

2.0 Study Area

The recently leased Carolina Long Bay offshore wind farm, located off the coast of southeastern North Carolina, forms the focus of this study (Figure 1). The Bureau of Ocean Energy Management (BOEM) auctioned off the Carolina Long Bay Wind Energy Area (WEA) to prospective developers on May 11th, 2022 comprising a 110,000 acre offshore region located approximately 31.5 km (17 nautical miles) offshore Bald Head Island, near the terminus of the Cape Fear River. The proposed OWF is expected to generate 1.3 GW of electricity, providing more than half a million households with power, creating thousands of local jobs, and generating hundreds of millions of dollars in economic revenue. The wind farm will require one or more export (power) cables, connecting the wind turbine substation to a shore-based location for subsequent energy distribution to land based sources (NCTPC, 2021).

For this study, the export cable 'area of interest' extends from Masonboro Island in the northeast to the South Carolina border in the west, and from the coast to as far as 40 km offshore (Figure 1). The proposed Carolina Long Bay OSW farm is located 31.5 km (17 nautical miles) off Bald Head Island from its closest point on shore. Coastal southeastern North Carolina comprises a number of developed and undeveloped north-south and east-west oriented transgressive barrier islands, separated by tidal inlets (Cleary, 2001; 1999; Shiflett and Backstrom, 2023). Tourism is a major source of income for the rapidly growing towns which are located along the coast. Tides are semidiurnal and microtidal, with a mean tidal range of 1.37 m off Bald Head Island (NOAA, 2023). A 10-year record of wave data obtained from Station 41108 - Wilmington Harbor, NC (NDBC, 2023) reveals significant wave heights (Hs) are approximately 1.0 m with an average dominant wave period (Td) of 7 seconds; mean wave direction is from the SSE (153 degrees). According to the National Renewable Energy Laboratory, average offshore wind speeds at 90 m elevation within the study area range between range 7.5 m/s at the coast to 9.0 m/s at the proposed wind energy area (NREL, 2023). Offshore wind resources in North Carolina are among the best in eastern United States and a relatively wide and shallow continental shelf makes it an ideal location for OSW farm development.

Southeast North Carolina lies directly in the path of North Atlantic tropical systems, and has been impacted by numerous hurricanes, most recently by Isaias (Cat 1 - 2020), Dorian (Cat 1, 2019), Florence (Cat 1 – 2018) and Matthew (Cat 1 – 2016) (Figure 1). Other destructive hurricanes include Bonnie and Fran (1995) and Category 4 Hazel in 1954. The offshore seabed region comprises numerous Plio-Pleistocene high- to low-relief carbonate hardbottom reefs, often overlain with a thin veneer of sand and gravel (Marcy et al., 1996; Cleary et al., 1996; Backstrom, 2002). Thick regionally expansive sand bodies are not

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common off southeastern North Carolina and are mostly limited to either localized ancestral paleo-river channel systems or large sand shoals located adjacent to and offshore of the Cape Fear River (Cleary, 1999; Riggs et al., 1995; Backstrom, 2002).

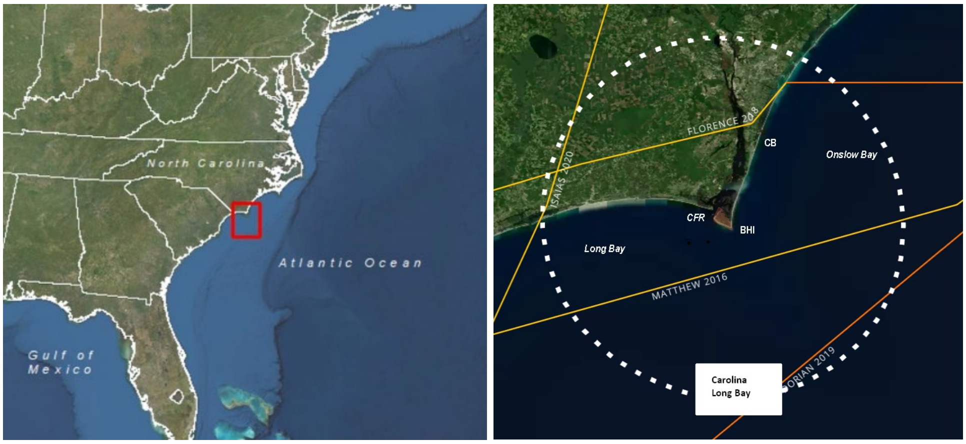

Figure 1: Study Area. The proposed Carolina Long Bay Offshore Wind Farm is located in the north Atlantic Ocean off southeast North Carolina, approximately 31.5km nautical miles south of Bald Head Island (BHI). Also shown are recent hurricanes that have impacted the area since 2015 (right). *CFR* refers to the Cape Fear River mouth and *CB* refers to Carolina Beach. Dotted circle radius is 25 nautical miles. Hurricane track data obtained from NOAA. Satellite image (right) courtesy of © Google Maps.

The area eligible for turbine placement covers slightly more than 110,000 acres and comprises BOEM's offshore wind lease areas OCS-A 0545 and OCS-A 0546 on the Atlantic Outer Continental Shelf, which were awarded to Total Energies Renewables USA, LLC and Duke Energy Renewables Wind, LLC, respectively. This area of southeast North Carolina has a range of protected species, coastal conservation areas, offshore reefs and historical shipwrecks. Additionally, the region is highly susceptible to tropical storms and hurricanes, has limited offshore sediment (apart from Frying Pan Shoals), is an important hub for both fisheries and shipping, and supports a multi-million-dollar tourism industry. The spatial arrangement and distribution of these multiple overlapping receptors across the study area make the routing, installation and operation of subsea power cables particularly challenging.

3.0 Methods

In order to quantify optimum routing and spatial mitigation measures for the export cable, this study used a three phased approach: i) A desktop study and literature review of publicly available coastal and ocean data for the region; ii) quantifying environmental sensitivity and risk based on standard EIA procedures and iii) using GIS-based spatial and modelling techniques to optimize route planning by combining heat maps and Euclidean Distance tools. Temporal and spatial mitigation techniques are also incorporated into the assessment.

The primary strategy in evaluating optimum cable routing for Carolina Long Bay was by means of an environmental heat map, in essence mapping the intensity of different receptors based on sensitivity (e.g. endangered species, essential fish habitat,

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protected areas) and areal extent or, conversely, assessing potential impacts to the integrity of the export cables (e.g. shipping and navigation areas). Using geospatial technology, operations were performed using ESRI’s ArcMap 10.8.2, which highlighted corridors exhibiting maximum distances from identified hazards. Before generating the heat maps, a thorough review of publicly available BOEM reports, relevant research, published papers, grey literature and other desktop studies was conducted. This allowed a strategy development for the heat map exercise and the choice of ideal data to use in the operations, while also carefully considering all the types of data available (Table 1).

Environmental review processes for offshore wind farm permitting and development consider a wide range of factors, including stakeholder consultation, scoping and environmental impact assessments/statements (BOEM, 2023). To minimize potential impacts from any proposed development, a variety of mitigation measures are required. Depending on the type of impact, often either spatial or temporal mitigation is chosen as the most appropriate option. Certain receptors were displayed in map figures but were excluded from spatial analysis. For these receptors, the most appropriate management measure does not involve spatial mitigation. Possible temporal mitigation measures or other mitigation strategies for these receptors are discussed in the Results section.

The spatial analysis to produce the heat map follows a basic workflow that was replicated for each GIS layer. Each layer that was included in the analysis was imported as a shapefile, which contained vector data within the GIS interface. The input layers were subsequently converted into individual raster files, with a 100-meter spatial resolution. As part of the project design, a risk value was assigned to each input, based on the anticipated impact from the installation of the export subsea cable to each receptor, or as a hazard to cable laying operations. Assigning risk values to sensitive receptors based on anticipated impacts is a practice that has been used in offshore wind planning before and is a common approach with Environmental Impact Assessments (Bergstrom et al., 2014; BOEM, 2023a). Marine spatial planning also incorporates many of the design components of our study, primarily by identifying suitable areas for specified uses in the marine environment through minimization of conflict (Lonsdale et al., 2020; Choi et al., 2021).

Risk values for our model ranged from one to three (Table 2). A value of ‘1’ was assigned to areas that, without proper avoidance, could lead to minor impacts on receptors, such as temporary area closures or obstacles to other ocean users. For areas where cable construction is expected to lead to major impacts on receptors, either human or ecological, a value of ‘2’ was assigned. Lastly, a value of ‘3’ was given to any areas that represent a major hazard or threat to the integrity of the cable structure itself or cable-laying equipment, or for regions under the jurisdiction of policies which disallow such infrastructure. These areas must be ‘avoided at all costs’ and in most cases, a sufficient spatial buffer/exclusion zone around the hazard must be adhered to. The following table identifies each of the GIS layers that were used as inputs and their associated risk values that were retained in the model (Tables 1 and 2).

Table 1: Data source(s) for each GIS Layer

Data Layer	Source

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Study Area	Arbitrarily determined by authors
Wind Energy Area Polygon	https://www.boem.gov/renewable-energy/state-activities/carolina-long-bay
Bathymetry (Ocean Reports)	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Bathymetry Contours (Ocean Reports)	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Bathymetry (GEBCO)	https://download.gebco.net/
East Coast Sediment Texture Database / ECSTD2014 Sample Points (USGS)	https://woodshole.er.usgs.gov/openfile/of2005-1001/htmldocs/datacatalog.htm
Continental Margin Mapping Program / CONMAP Sediment Size Distribution Polygons (USGS)	https://woodshole.er.usgs.gov/openfile/of2005-1001/htmldocs/datacatalog.htm
F00679 Backscatter Data (NOAA)	https://www.ngdc.noaa.gov/nos/F00001-F02000/F00679.html
H11413 Sidescan Data (NOAA)	https://www.ngdc.noaa.gov/nos/H10001-H12000/H11413.html
H12930 Backscatter Data (NOAA)	https://www.ngdc.noaa.gov/nos/H12001-H14000/H12930.html
Essential Fish Habitat (NOAA)	https://www.habitat.noaa.gov/protection/efh/newInv/index.html
Habitat Areas of Particular Concern (NOAA)	https://www.habitat.noaa.gov/protection/efh/newInv/index.html
Cetacean Biologically Important Areas (Ocean Reports)	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Audubon Important Bird Areas (Audubon Society via Ocean Reports)	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Coastal Barrier Resource Areas	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4

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Protected Areas	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Danger Zones	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Shipwrecks	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Artificial Reefs	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Navigation Channels	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Shipping Lanes	https://marinecadastre.gov/oceanreports/#/@-10737743.881037742,4753280.983019757/4
Hardbottom/Essential Fish Habitat Areas	Digitized from Captain Seagull's Fishing Chart

Risk values were incorporated into the raster file for each layer by means of the Reclassify tool in ArcMap, which allowed each raster layer to have the risk level populated as its cell value for each cell in the raster. These individual files were subsequently combined into one raster layer covering the entire extent of the study area using the Raster Calculator tool. A blank raster with identical cell sizes and a value of 0 for each cell was added to the operation to function as a background, allowing the output to cover the entire extent of the study area. The output from this tool created a composite heat grid, displaying a value for each cell that represented the total risk associated with that space. Cells that did not contain any hazards or did not overlap with any receptors retained a value of '0', indicating no environmental risk. The heat grid was symbolized according to cell value, highlighting differences in risks associated with export cable operations across the entire study area.

The composite heat grid was used as an input for the Euclidean Distance tool to reveal microregions within the study area likely to exhibit minimized impacts to the cable and surrounding environment. With a broad understanding of the distribution of risk factors within the export cable region, possible export cable corridors were digitized according to the maximum distance from surrounding hazards. Though one of the options intersects an area with a nonzero risk value, it only interfaces with an area that displays minimal risk and adjusts course for the adjacent option in the manner of reducing several miles of cable

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length. This option was put forth as a consideration to engage in a trade-off between taking on a low level of impact while implementing savings in terms of cost and length of the overall export cable project.

Table 2: Associated risk values for each layer/sensitive receptor. Value was based on standard EIA/NEPA policy according to BOEM and authors' best judgment.

Layer Inputs for Heat Map	Associated Risk Value
Anchorage Areas	2
Artificial Reefs and Natural Hardbottom	3
Shipping Lanes	1
Coastal Barrier Resource Areas	3
Danger Zones and Restricted Areas	3
Protected Areas	3
Navigation Channels	2
Ocean Disposal Sites	2
Shipwrecks	3

Risk Value Key:

1 - Without avoiding this area, minor impacts are expected (shipping lanes)

2 - Without avoiding this area, major impacts are expected (anchorage areas, ocean disposal sites, navigation channels)

3 - This area must be avoided entirely; contains hazards with the potential to compromise equipment / cable itself; regulations prevent cable laying operations in this area (danger zones/restricted areas; protected areas; shipwrecks/artificial reefs)

4. Results

4.1 Physical Environment

The initial results of the case study reveal several key marine environmental characteristics in which the proposed offshore wind project is set to take place. With the northernmost extent of the Wind Energy Area located 31.5 km south of the nearest shoreline on Bald Head Island, a substantial area of seabed must be assessed in order to install the export cable. One of the

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most prominent feature of this offshore area is the Frying Pan Shoals, a 45-km stretch of sand waves and shallow shoals that measure as little as 3 meters deep in some offshore areas between the WEA and the closest onshore location (Figure 2). Water depths in the rest of this offshore region range from less than 10 meters nearshore and along the shoals up to slightly more than 30 meters.

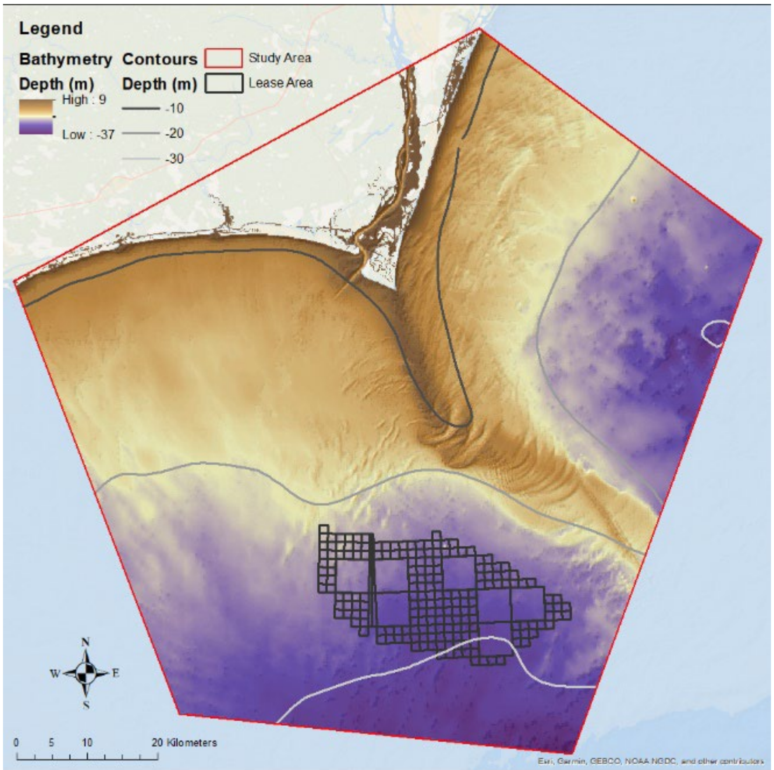

Figure 2: Water depths within study area. Note extensive sand shoals extending towards the southeast associated with Frying Pan Shoals, classified as essential fish habitat.

The bathymetric data and contours displayed in this figure clearly display the extent of the Frying Pan shoals, as well as sand wave fields to the north of the WEA, on the western side of the shoals. Assuming the shallowest of these features are avoided during cable-laying operations, most of the seafloor area that must be covered by the cable falls between 10 and 20 meters below the surface. Bathymetry data is particularly useful in determining the equipment type and installation methods for the export cable.

According to the USGS surface sediment database, the seabed sediments within the study area are primarily composed of sand (yellow), although shells and mud (green), in addition to rock and gravel (orange) is also present (Figure 3). A good understanding of sediment cover is especially important when it comes to cable installation methods, in addition to installation vessel anchoring/mooring methods and general benthic characteristics.

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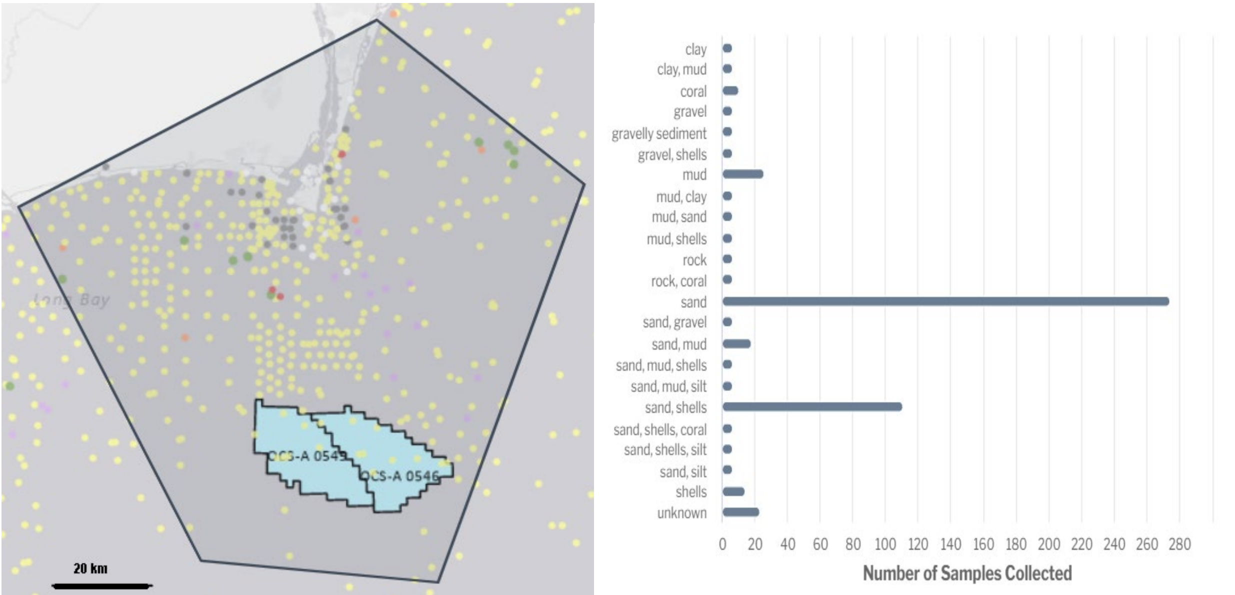

Figure 3: Surficial seabed sediment distribution. Most of the region is comprised of sand, although mud and shells are also common (Source: USGS). Sediment thickness and the presence of hardbottom reefs is not shown in the figure.

The presence of natural hardbottom reefs (likely identified as 'rock' sediment) throughout the study area is well known and an important factor to consider in cable routing. Hardbottom, also characterized as essential fish habitat, will be discussed separately under Biological Resources.

Previous seabed surveys within Long Bay in the late 1990's, which included extensive sidescan sonar, vibracores and surface sediment sampling, revealed that the shoreface was not a viable source of long-term compatible beach nourishment sand, instead mostly comprising a mix of thin, muddy sediment layers or hardbottom outcrops (Cleary et al., 2001). The only well-known thick sand bodies include Jay Bird and Frying Pan Shoals, located adjacent to or offshore the Cape Fear River inlet respectively.

4.2 Biological Resources

The marine environment encompassed by the study area, including some of the coastal areas that could be impacted by the cable landfall location, serve as important habitat for a variety of fish, birds, and mammals (Taylor et al., 2016; BOEM, 2022b). Large sections of the study area are classified as Essential Fish Habitat (EFH) by NOAA. Habitat Areas of Particular Concern (HAPC's) are a subset of EFH that provide especially important ecological functions or face increased vulnerability to degradation. Much of the study area consists of zones that are designated as Habitat Areas of Particular Concern (Figure 4).

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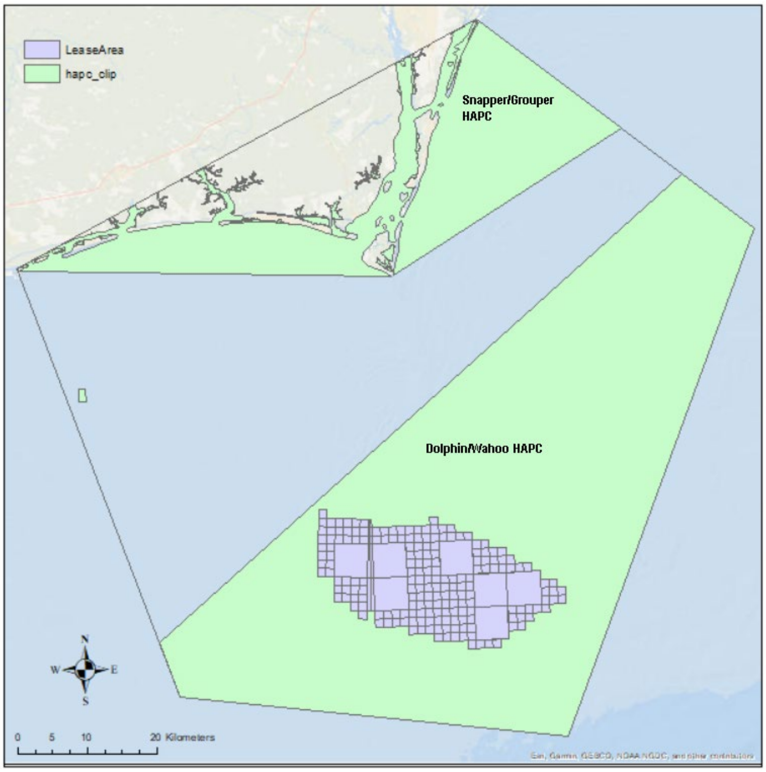

Figure 4: Habitat areas of particular concern (HAPC's), which include dolphin, wahoo and snapper/grouper.

The HAPC's in Figure 4 represent habitat for pelagic species, such as Dolphin (*Mahi Mahi*) and Wahoo, in addition to commercially important demersal fish species, such as Snapper and Grouper. Parcels of essential fish habitat (i.e. hardbottom) are also dispersed throughout the study area. Not only do these areas represent important habitat for benthic and fish species, but they also present a challenge to export cable burial capabilities due to the presence of sub-cropping or outcropping rock on the seabed.

In addition to fish, the study area contains habitat for other classes of marine vertebrates, most notably marine mammals, sea turtles, and birds (Figure 5). Biologically Important Areas (BIAs) for prominent Cetaceans are known to inhabit the area, especially the North Atlantic Right Whale (NARW) and Bottlenose Dolphins. Important coastal bird areas, as designated by Audubon, are also included.

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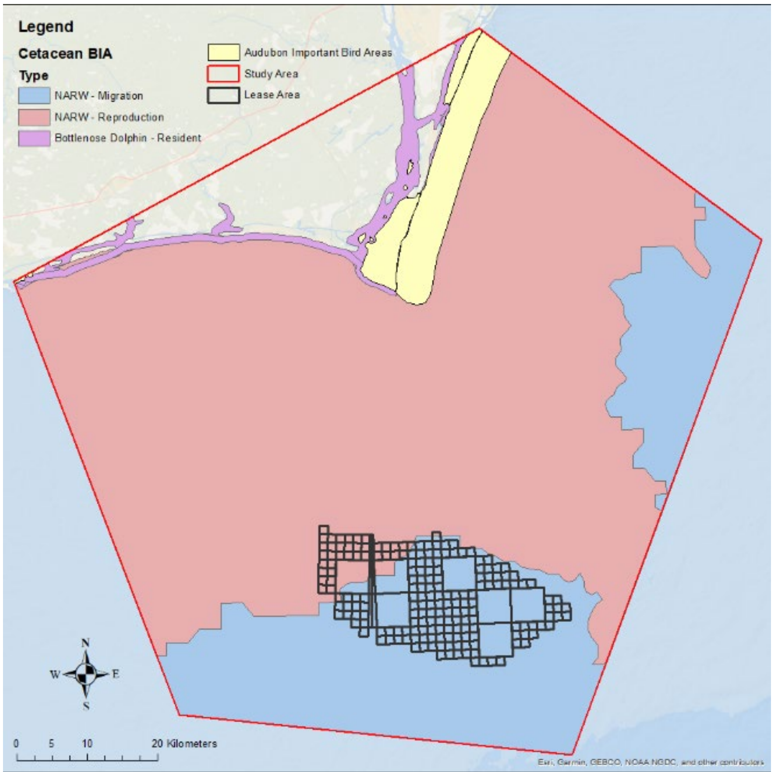

Figure 5: Marine mammal migration areas, especially North Atlantic Right Whale (pink), resident bottlenose dolphins (purple) and designated Coastal Bird Areas (yellow).

In order to mitigate the effects of export cable installation on NARW migration routes, *temporal mitigation* (i.e. avoiding construction activities when they are known to be present in the region) is recommended. The cable route is also highly likely to overlap with Bottlenose Dolphin resident areas and has the potential to impact important bird areas if landfall is made along the shoreline north of Bald Head Island. Another environmental designation that is relevant to cetacean distribution is the North Atlantic Right Whale Seasonal Management Area (SMA). This is a designated offshore zone that restricts the speed of large vessels during certain months of the year, when Right Whales are known to migrate off the coast of North Carolina (Figure 6).

4.3 Regulated Areas and Obstructions

Landfall location is an important aspect of the design process for export cable routing. The transition between marine and terrestrial environments presents a unique engineering challenge. Additionally, much of the shoreline within the study area is subject to prohibitive regulations which must be planned around carefully. In addition to protected natural areas, there are large tracts of land that are subject to the Coastal Barrier Resources Act (CBRA), which prohibits development and a variety of other anthropogenic activities. There are also restricted areas along the western shoreline of the lower Cape Fear River, classified as danger zones and strictly reserved for governmental and/or military uses. In terms of mitigation, these restricted

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areas must be circumvented or avoided using *spatial exclusion zones (*i.e. establishing a no-go boundary*)* when planning the export cable route.

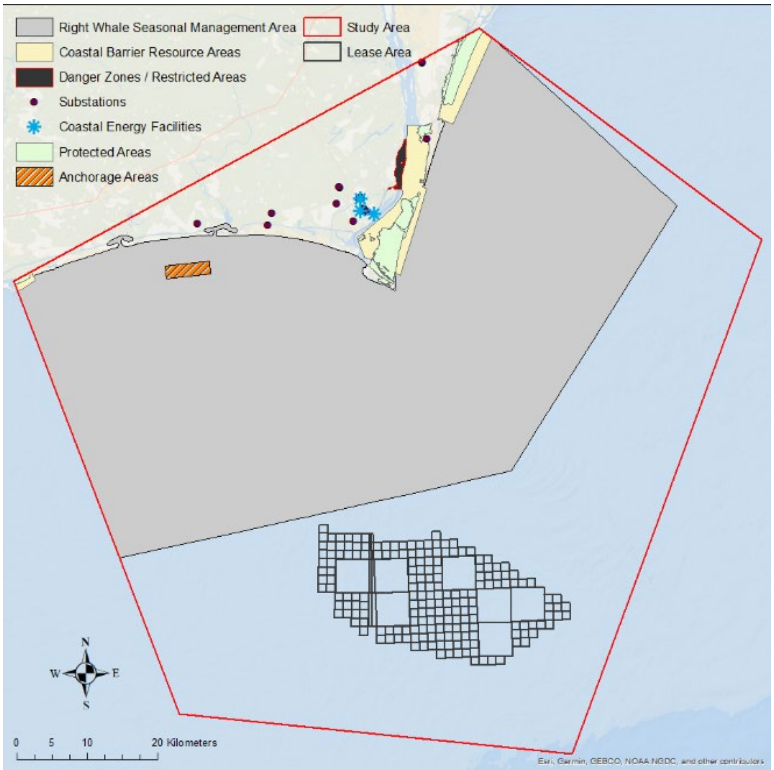

Figure 6: Right Whale SMA, terrestrial protected areas, restricted areas, anchorage areas, substations and coastal energy facilities (landfall focus).

Other constraints to cable routing come in the form of physical obstructions on the seafloor. These include shipwrecks (many of which date back to the Civil War era, e.g. Blockade Runners), natural 'essential fish habitat' hardbottom areas, artificial reefs and ocean disposal sites (Figure 7). Areas dominated by rubble or coarse gravelly sediment, often located adjacent to the hardbottom reefs, may also present challenges to cable-laying operations.

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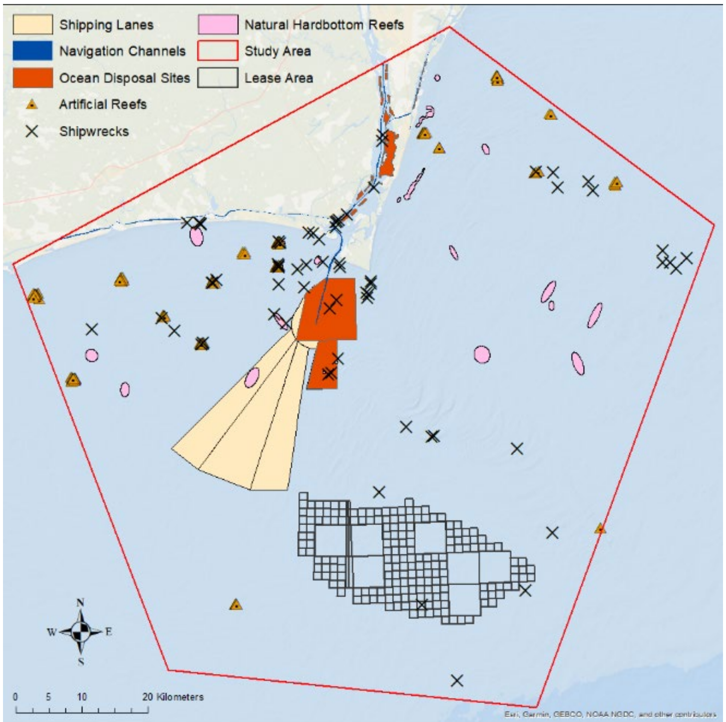

Figure 7: Shipwrecks, hardbottom (essential fish habitat) areas, artificial reefs, obstructions and navigation routes.

Hardbottom reefs are especially prevalent in the region, but due to limited seafloor mapping and the sub-cropping nature of these features, in many cases covered with a thin veneer of sediment, mapped and confirmed reefs undoubtedly only form a small fraction of the total area present within the region (Cleary et al., 1996, 2001; Taylor et al, 2017). Not only do these areas represent important habitat for benthic and fish species, but they also present a challenge to export cable burial. Recent Carolina Long Bay informational stakeholder workshops held by BOEM suggest that the hardbottom areas are of significant concern for many recreational and commercial fishermen, often targeted due to the presence of valuable fish stocks.

Navigation presents another challenge to cable routing. With the deep-water port of Wilmington located approximately 35 km up the Cape Fear River, many large vessels make their approaches to the port in the offshore area near the WEA (Figure 7). There are also anchorage areas located near the Cape Fear River Inlet which present a direct risk to the proposed export cables, due to anchoring risks which may compromise structural integrity. An additional navigation and cable routing constraint is the broad footprint of the Traffic Separation Scheme (TSS). Vessels making their approaches to the port are required to remain within a designated shipping lane that covers a particularly large area and happens to be located between the wind farm location and several potential landfall sites. Although avoiding navigation areas are not a requirement for cable routing, running an export cable through any part of the TSS will lead to temporary area closures which may have social and economic impacts on the local shipping industry. Proper cable burial will be critical within these TSS areas to prevent any kind of cable exposure or free span, which has been known to occur at a few windfarm sites in Europe (English et al., 2017).

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Environmental Heat Maps

This section provides a summary of the GIS-based heat maps, delineating high-risk versus low-risk areas for cable routing, based on environmental constraints. A composite heat map of physical constraints, which include reefs, wrecks, navigation areas, protected sites and military locations (Figure 8) shows specific areas of environmental constraint which represent a high composite risk score. There are several areas that contain scores of 3 to 4, which in many cases represent hardbottom reefs within the proposed export cable region and present substantial installation/burial and integrity risk for the cable. Areas with a score of 4 or higher in many cases represent areas that contain overlapping hazard areas. In both cases, there is high potential for the identified hazards to hinder export cable routing and therefore these areas should be avoided.

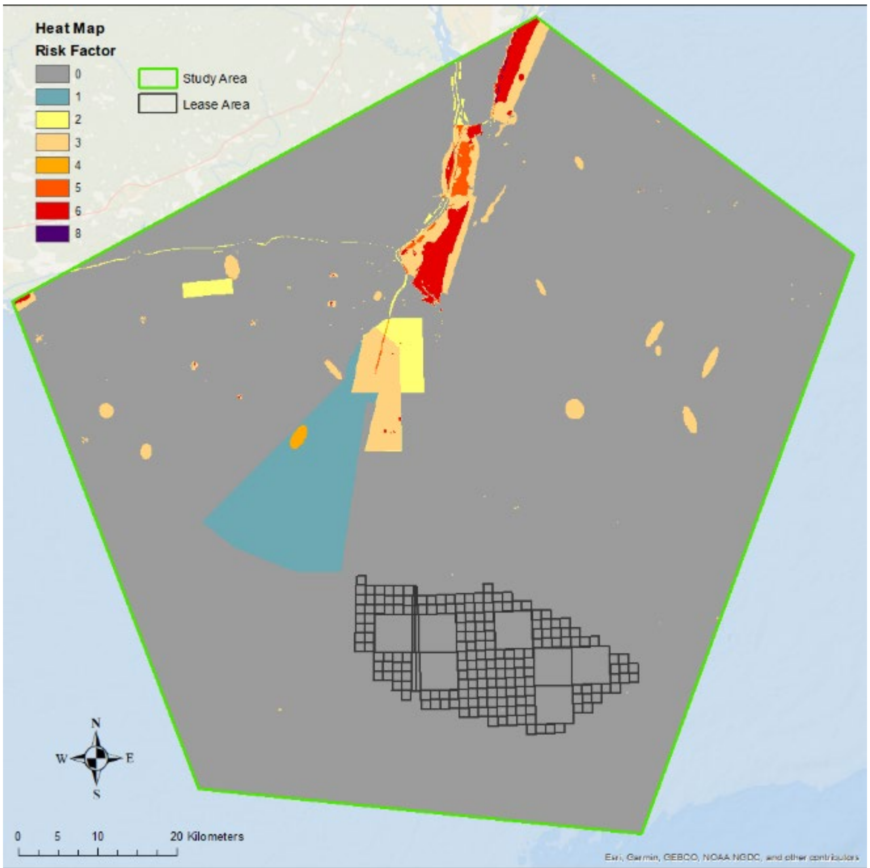

Figure 8: Composite raster heat map of selected constraints to export cable routing and installation.

The most restricted 'high risk' zone, based on the combined risk value of all the hazards in the area, extends from most of Bald Head Island north towards Carolina Beach State Park. The protected areas within this region include State Natural Areas, Coastal Reserve sites, Coastal Barrier Resource Areas, a state park, and a military operations zone. These multiple protected nature and military 'no go' areas may have significant implications for the export cable planning and installation. By avoiding

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certain high-risk areas, cable re-routing will undoubtedly increase capital expenditure and operating costs for the offshore wind energy developers, which is a common experience as they navigate complex environments and engage with key state, federal and regulatory stakeholders (e.g. military, fisheries, conservation agencies) early in the planning phase.

A review of the composite raster heat map (Figure 8) and possible cable routes would suggest an optimal preliminary route might be installing the export cables up along the eastern side of Frying Pan Shoals and Bald Head Island, parallel to the shoreline of the southern beaches of New Hanover County. With an electrical substation located in the northern half of developed Carolina Beach, the export cable could make landfall near this site while avoiding protected coastal areas. The trade-off in this scenario is the requirement of a longer cable, (i.e. it is not the shortest route to land) with the additional caveat that the cable route begins on the eastern half of the WEA, allowing for complete or partial avoidance of Frying Pan Shoals, classified as essential fish habitat. Thick sand bodies are ideal for cable burial, which would be advantageous for the proposed export cable route; however large mobile bedforms may result in cable free-span or exposure with possible impacts on cable integrity and energy transmission. In addition to a standard heat map, a Euclidean distance analysis map generated in ArcGIS (Figure 9), represents proximity to potential hazards and environmentally sensitive locations. This modelling tool allows an overview of physical constraints based on distance and helps establish possible exclusion areas around areas considered 'no go' or high risk, which include for example shipwrecks, military facilities, reefs and protected areas.

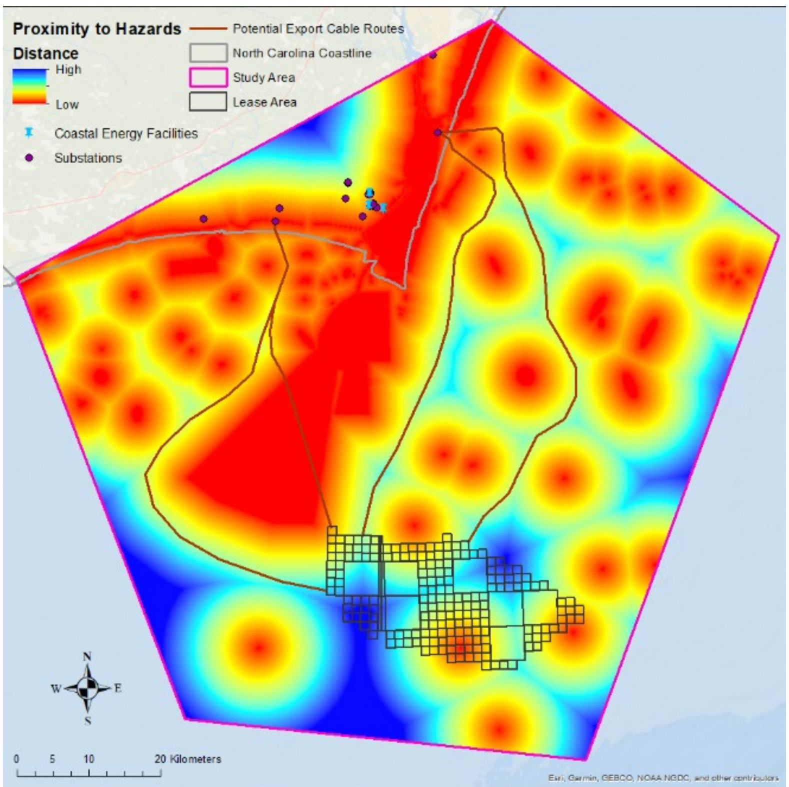

Figure 9: GIS-based Euclidean distance results showing areas of minimal risk (dark blue to light blue), high risk areas (yellow and red) and optimal export cable routes to minimize impacts.

Two potential substations present themselves as the most likely coastal export cable landfall destinations, which is an important consideration when planning cable routes, allowing a direct connection to the electrical grid. Each substation is located on either side of the Cape Fear River mouth and are the closest in proximity to naturally presented corridors from the WEA, while also maximizing distance from hazards along the entire route. Substations were also selected on either side of the Cape Fear River due to the dual leases awarded to energy developers.

With two companies awarded part of the lease area, planning two separate projects complicates the operation, particularly with export cable routing. The developers retain the option to run each of their export cables parallel to one another along the same corridor, eventually making landfall at the same electrical substation. Alternatively, the export cable routes could start from opposite ends of the WEA and take entirely different paths to different landfall locations several miles from one another. This second possibility seems more likely based on our examination of the layout of the region as part of the case study.

Figure 9 shows four cable route options on either side of the Cape Fear River and Frying Pan Shoals. These routes were developed based on the favourable areas displayed by the hazard proximity modelling data, with the exception of the shorter potential cable route in the western half of the study area. Acknowledging that this route cuts through an area of nonzero risk, it was selected based on the fact that it only interferes with the Traffic Separation Scheme. Crossing through these shipping areas will likely lead to temporary area closures during installation, creating impacts remain primarily human. Assuming proper cable burial, the risk is greatly reduced, and the structural integrity of the cable will not be endangered by anchoring activities. Running an export cable along this shorter route would reduce the cable length by up to 40% when compared to the adjacent route that completely circumvents the Traffic Separation Scheme. Though there is a substantial trade-off for each of these scenarios, providing several options allows the developer to weigh the benefits and drawbacks of each scenario.

5. Discussion

The results of this GIS-based modelling and desktop study provide important preliminary insights into the environmental characteristics of the project area and implications for export cable routing. From a high-level, early cable planning perspective, the results are promising. The study provides an overview of key marine spatial planning (MSP) constraints, including important coastal and marine areas that should be avoided due to high-risk.

Early phase MSP, to minimize conflict with other sea- and seabed-users, has been an important tool used by wind developers and government since the early days of offshore wind development, particularly in the UK and western Europe (Douvere and Ehler, 2010; Berkenhager et al, 2010; Jay, 2010; Gimpel et al, 2015) but also in the United States, e.g. offshore New York (Haaren & Fthenakis, 2011). Many of these studies used GIS and modeling techniques to map potential conflict areas, particularly for fisheries, dredging areas, cables and pipelines, shipping & navigation areas, MPA's and military locations. Other studies, where wind farms are being planned, continue to use MSP techniques and sea-user modeling methods to identify optimum locations for offshore wind areas, including off Taiwan (Zhang et al., 2017), Spain (Rodríguez-Rodríguez et al, 2016; Abramic et al., 2021) and the Baltic Sea (Göke & Mohn, 2018).

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Although there are numerous published papers examining the effects and ecological impacts of offshore wind farms, there are far fewer which focus specifically on subsea power cables (Taormina et al., 2018). Case studies, such as this one, which combine potential export cables routes, EIA principles, MSP and GIS modeling studies for planning purposes are not readily found in the published literature. Undoubtedly there are private engineering and environmental consultancy companies which use similar techniques, but these studies are not readily available most likely due to commercial sensitivities.

In most cases, including in this study, the potential cable route corridor area often exceeds the proposed wind energy development area. The competing marine user interests within this larger space between the main wind energy area/production site and the coast are more numerous, complex and varied (e.g. nearshore dredging and disposal sites, navigation channels, inlets and shoals, coastal MPA's, reefs and shipwrecks, coastal homeowners, important commercial and recreational fishing areas, tourism, beach erosion). In essence, this GIS-based modelling desktop study provides a relatively easy, fast and inexpensive method of identifying potential offshore wind cable corridors, which can be adopted not only by other wind developers, but also similar marine industries like subsea telecoms and pipelines.

It should be noted that a detailed study of each 'receptor' that may be impacted by cable installation or operation across southeast North Carolina is beyond the scope of this study. Instead, the study should be viewed as an important 'high-level' initial phase to identify larger ecological and physical constraints to cable routing. Following is a brief discussion of three priority environmental considerations when planning the cable route for the Carolina Long Bay wind farm. These include: i) cable burial, ii) hardbottom reefs/essential fish habitat and iii) coastal landfall locations. The complex geology of southeast North Carolina's shoreface/inner shelf and the variety of sensitive coastal characteristics makes these environmental constraints especially important when planning the cable route.

5.1 Export Cable Corridor/ Burial

The original Carolina Long Bay Environmental Assessment (EA) by BOEM in 2015 suggested that there be at least two to three 300 m wide export cable corridors per lease area, comprising approximately 155 km of surveyed cable route. To date, no specific export cable route corridor or land-based substation connection has been established, although the leaseholder will be required to identify the optimum corridor as part of their Construction and Operations Plan (COP).

When it comes to detailed seabed and subsurface studies to inform export power cable routing and installation, high-resolution geophysical (e.g. multibeam bathymetry, side scan sonar and seismic profiling) and geotechnical surveys are critical to inform final cabling design plans. They are, however, extremely expensive and time-consuming. This case study has been able to procure useful information at a significantly lower cost, and importantly the results can be used to optimize survey areas for subsequent geophysical and geotechnical (G&G) data collection, especially areas of the seabed that allow for proper cable burial (i.e., at least 1-2 m of unconsolidated surface sediment). Export cable corridors that mitigate the environmental impacts and avoid both hazards and restricted areas, can become the focus of subsequent G&G surveys. The data collected as part of this study will allow fine-tuning of potential survey corridors areas, thereby reducing cost and time.

5.2 Essential Fish Habitat/Hardbottom

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The hardbottom reefs and associated nearby features are protected under the Magnuson Stevenson Fisheries Act, and are designated as Essential Fish Habitat (ESH) by the National Marine Fisheries Service (NMFS). The widespread presence of EFH on the shoreface and inner shelf has been well documented along the sediment-starved southeast coast of North Carolina (Cleary et al, 1996; Riggs et al, 1995, 1998; Backstrom, 2002). Although the prevalence of hardbottom reefs is well known, the distribution, 3-dimensional architecture abundance and ephemeral nature of the reefs is still not well established (Riggs et al. 1995, 1998; Cleary et al., 1996; Taylor et al., 2017). Figure 10 shows a sidescan sonar image of a hardbottom reef located off southeast NC, illustrating the complexity of these environments, which can range from high-relief carbonate/limestone outcrops to rubble fields to featureless fine sand. Some estimates suggest that only 10% of the outer continental shelf of southeast NC has been mapped using modern geophysical and geotechnical (G&G) survey methods, resulting in a lack of knowledge regarding the presence of these ecologically important areas (Taylor et al., 2017). The reefs comprise high-biodiversity areas, and are known to attract and provide critical habitat to numerous fish and benthic species (Quattrini et al. 2004, Kendall et al., 2009; Freshwater et al, 2016). They are also important locations for commercial and recreational fishing and diving activities.

Stakeholder concerns include identifying all hardbottom habitat within 300 m of the windfarm and associated infrastructure, including cables, in addition to mapping smaller hardbottom units. As part of the leasing process, BOEM requires benthic habitat surveys to inform site characterization in order to assess potential environmental impacts (BOEM 2015b; Final SEA, 2022b). As with cable burial, high resolution G&G surveys will be critical to identify and map EFH areas, where cable burial is not possible.

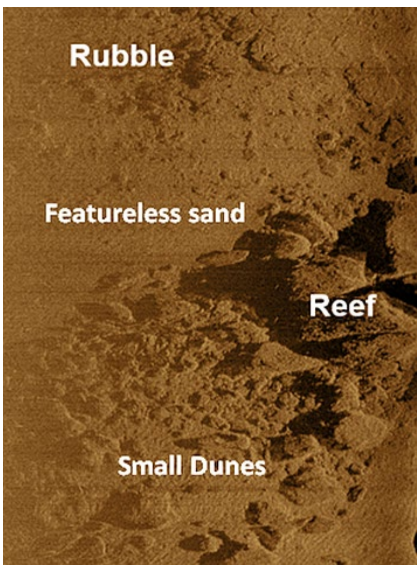

Figure 10: Sidescan sonar (acoustic) image of hardbottom reef and surroundings from southeast NC. Note mix of seabed types, including high-relief reef, rubble, small dunes/bedforms and featureless sand. Cable burial through a location like this would not be feasible due rock presence and limited sediment thickness. Image by J.T. Backstrom.

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5.3 Export Cable Landfall

The coastal zone where the export cables potentially make landfall includes the east-facing New Hanover and south-facing Brunswick County beaches, separated by the Cape Fear River mouth. As a result, there are multiple environmental constraints within this area, which include e.g., important bird areas, coastally significant geological areas, EFH, shipwrecks, wetlands, critical fisheries habitat and coastal barrier resource (protected) areas. Navigating these multiple inland, coastal and marine areas, coupled with identifying a likely electrical substation, presents a challenge to optimal landfall locations. A preliminary assessment from this study identified two potential landfall locations. The first location routes the export cables towards the Brunswick Nuclear Power Plant utilizing the coolant canal that drains just offshore of Caswell Beach (Figure 11). This route avoids wetland habitats and coastal barrier resources, such as Bald Head Island Nature Conservancy and Fort Fisher State Park. The environmental impact on wetlands would be negligible to minor since the area has already been developed. Insulation methods such as a sediment cap or concrete layering would prevent cable damage due to abrasion. Additionally, tethering the cable would prevent damage. The cables' heat resistance would allow it to be submerged within the canal or buried alongside the canal route.

The second optimum landfall is located within developed central Carolina Beach, where there is an existing sub-station on shore. Areas further south are mostly protected coastal barrier or geologically/archaeologically important areas (Bald Head Island, Zeke's Island, Fort Fisher). The developed nature of Carolina Beach would limit potential impacts to sensitive habitats like wetlands and seagrasses, which are common in the surrounding areas. There will be temporary human impacts in terms of beach closures and access during the short landfall construction/burial phase, which can be easily minimized by temporal mitigation techniques (e.g., avoiding construction during the busy tourist season).

Figure 11. Possible location for export cable landfall adjacent to the coolant canal for Brunswick Nuclear Power Plant. Environmental constraints would be minimal here due to the already developed/engineered nature of the location. *Source: NOAA.*

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Additional studies that conduct biological monitoring of potentially impacted areas will assist with the planning process. Enhanced understanding of the species present and their response to export cable installation will allow for fine-tuning of the environmental review process. Long-term monitoring is a necessary component of such studies, since the export cable has the potential to permanently alter the seabed if not removed after the decommissioning phase. For impacted ecological communities, examining their response to newly established environmental conditions associated with the cable will provide valuable insight into the long-term effects on marine ecosystems. These types of studies will improve environmental mitigation practices that can be implemented at other planned offshore wind projects and similar subsea industries, like pipelines and telecommunications.

6. Conclusions

This GIS-based environmental modelling desktop mapping study has been effective in identifying initial environmental project constraints with easily available desktop and literature review resources. Similar desktop studies using GIS are common for offshore wind projects, although to date studies focused exclusively on export cables and optimal routing using standard EIA methods, are not readily apparent in published literature. Undoubtedly similar approaches have been used by private engineering and environmental companies, where commercial sensitivities likely ensure the resulting studies are not publicly available.

The lack of site specific high-resolution environmental survey data may be the greatest challenge to early export cable routing and site-selection. When it comes to subsea power cables, the main way of avoiding a number of potential impacts (EMF, thermal, entanglement, structural integrity) is through proper cable burial into the seabed, which is ideally at 2 m depths for offshore wind farms (English et al., 2008; Worzyk, 2009; OSPAR, 2012; Taormina et al, 2017; BOEM 2023a). Once spatially defined high-risk areas have been delineated and avoided (e.g., via well-defined exclusion zones), a solid understanding of seabed surface and substrate characteristics is essential. Extensive high-resolution geophysical, geotechnical and sedimentological surveys, especially sidescan sonar, shallow seismic profiling, cone penetrometer testing and coring data, which identify seabed and sub-seabed characteristics on a much smaller scale, is required for optimal cable installation and route selection. These marine survey techniques also inform benthic characteristics and are also able to identify anthropogenic features such as shipwrecks and cables/pipelines.

The factors that are considered for environmental impact assessments pertaining to offshore wind export cables are both numerous and diverse. A wide variety of sensitive receptors exist in the offshore area between the Carolina Long Bay wind energy leasing areas and the nearest shorelines that contain possible landfall sites for the export cable. While the impact to many of these receptors and hazards to the export cable can be minimized or avoided using spatial mitigation techniques, some receptors will require temporal mitigation to generate the lowest possible impact. Impacts to the physical environment can generally be accounted for and mitigated spatially, while in most cases biological resources tend to have a less defined location due to the migratory nature of many species found in the coastal ocean environment.

Though the case study reveals clear "no go zones," there are limitations in terms of the hazards and potential impacts that can be revealed without field surveys. There may yet be additional impacts associated with the selected cable routes that the case study was unable to identify. However, delineating the areas with a known hazard or anticipated major impacts will allow future surveys to focus only on the viable areas, without known hazards or restrictions. The methods employed in this case study can be used at other wind farm projects, as a productive step in early marine spatial planning for export cabling. The marine environment off the coast of North Carolina presents an excellent opportunity for offshore wind development, but sustainable use of this resource has been made a clear priority by the state and federal government. Mitigation strategies for export cables, as shown in this study, can be implemented to ensure that one of the most important components of an offshore wind operation has a minimal impact on marine and coastal resources.

Competing Interests

The manuscript authors have no conflicts or competing interests to declare. All authors have contributed to, and agree, with the contents of the manuscript. We certify that the submission is all original work and is not under consideration for publication at any other journal.

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Author Contributions

JT Backstrom: original study concept, literature review, data mining, writing, analysis, figure production, submission.

NM Warden: literature review, GIS analysis, modeling, data mining, writing, figure production.

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