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Geospatial Analysis of Technical and Economic Suitability for Renewable Ocean Energy Development on Washington's Outer Coast

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June 2013

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Prepared by
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Prepared for
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June 2013

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Summary

To support the State of Washington's marine spatial planning efforts, the Pacific Northwest National Laboratory (PNNL) and Parametrix were asked to conduct a spatial analysis of basic siting factors to determine where marine renewable energy development may be feasible on the Washington coast. The scope of the study includes tidal, wave, and offshore wind power generating technologies. The devices we selected to represent these technologies are the core device types anticipated to be commercially-viable in the Pacific Northwest. The scope includes projects that would commence a planning or feasibility phase within the next five to seven years. This time horizon serves to narrow the focus to existing, tested technologies deployed within a few miles of shore, with the exception of offshore wind floating platform technology which would most likely be deployed within 20 miles of shore.

This study uses a multi-criteria decision analysis framework of weighted additive algorithms to evaluate site suitability. Attributes of suitability used in this analysis represent fundamental economic and technical feasibility considerations and include energy potential, water depth, proximity to shore, ports, and transmission infrastructure. Socioeconomic, legal, regulatory, national security, and environmental factors—key factors to consider in planning for renewable energy development—are beyond the scope of this study. The separation of fundamental suitability factors from other considerations influencing marine spatial planning is intentional and intended to respect Washington State's stakeholder-informed planning process.

We developed conceptual models to organize attributes of suitability. Eight models were needed to represent the breadth of existing ocean energy generation devices suitable for Washington coast deployment. Available literature and expert advisors familiar with the industry, technologies, and devices informed the application of scores and weights to attributes for each model. Additive algorithms enabled a numerical translation of composite suitability that could then be represented spatially in a geographic information system. At the same time, we developed a geospatial database for the Washington coast containing available geospatial datasets corresponding to attribute suitability and based on Bureau of Ocean Energy Management's (BOEM) Outer Continental Shelf (OCS) leasing blocks. The dataset divides each BOEM block into sixteen, 1.44 square kilometer (0.56 square mile [mi^2]) sections, for a total of 24,291 units (referred to as aliquots). These are the minimum units for this analysis, and are what is referred to as sites within this report. Multiple sites comprise areas of suitability.

The results of this analysis are represented in a series of eight maps depicting suitability for tidal, wave, and offshore wind devices. Results suggest that there is a wider range of sites with higher suitability scores off the southern half of the Washington coast than the northern coast, although results differ based on device type. Fixed foundation wind energy models and nearshore wave device models closely followed this pattern, though it is less distinct in the mid- and deepwater wave model results. Most areas with high suitability occur within 25 miles or less of the coast. Results also suggest that the Washington coast has limited areas suitable for tidal energy development.

This study provides the base data layer—siting suitability based on technical and economic attributes—needed to inform planning for this potential new use of Washington coastal waters. The data identify areas meeting basic feasibility requirements for ocean energy that, if developed, may create conflict with existing uses. The results of this study are in no way intended to serve as a recommendation for project siting. Rather, these results are designed to inform a comprehensive marine spatial planning process that considers existing and future ocean uses against local and regional priorities.

This suitability analysis approach was first developed by Oregon Wave Energy Trust and Parametrix to evaluate wave energy development off the Oregon coast (OWET 2009, 2010).

Acknowledgements

The authors acknowledge the Washington Department of Natural Resources for funding this project, Katrina Lassiter and Jennifer Hennessey for guidance and constructive feedback, and the Washington Coastal Marine Advisory Council for their review and suggestions for how to make this work relevant to marine spatial planning efforts on the Washington coast.

Completing this work involved soliciting input from a group of industry advisors to inform suitability conceptual models; the advisory group included Oregon Wave Energy Trust (OWET) staff and representatives of wave, tidal, and offshore wind developers. Their input was critical to informing and prioritizing the model parameters. This approach was built upon work carried out by Parametrix and OWET to map wave energy feasibility used to inform the State of Oregon in their process of amending its Territorial Sea Plan.

The team is grateful to the expert advisors, industry representatives, OWET, the statistical guidance of Dr. Valerie Cullinan at PNNL, model development assistance and advice by Jim Koloszar and Kevin Halsey at Parametrix, and peer reviewers at PNNL (Jennifer States, Jeff Ward, and Dr. Ron Thom) for their involvement in this project.

Acronyms and Abbreviations

BOEM	Bureau of Ocean Energy Management
CMSP	Coastal and Marine Spatial Planning
DNR	Washington Department of Natural Resources
DOE	U.S. Department of Energy
FERC	Federal Energy Regulatory Commission
GIS	Geographic Information System
km^2	square kilometers
kW/m^2	kilowatts per square meter
MCDA	multi-criteria decision analysis
MHK	Marine and Hydrokinetic Energy
mi^2	square miles
nm	nautical miles
NNMREC	Northwest National Renewable Energy Center
NREL	National Renewable Energy Laboratory
OCNMS	Olympic Coast National Marine Sanctuary
OCS	Outer Continental Shelf
OWET	Oregon Wave Energy Trust
PNNL	Pacific Northwest National Laboratory
PUD	Public Utility District
UW	University of Washington
WCMAC	Washington Coastal Marine Advisory Council
WEC	Wave Energy Converter

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1 Introduction

The nation, regions, and states are engaged in planning processes that seek to align the multiple uses of ocean space to aid management of both existing and emerging uses. Marine renewable energy is a new use that in many cases is driving planning processes around the country.

At the direction of the Washington State Legislature, Washington State is engaged in coastal and marine spatial planning (CMSP) activities on the Pacific Coast. Anticipating future potential interest in offshore wind, tidal, and wave energy, the State Legislature directed agencies, tribes, and coastal stakeholders engaging in the planning process to include plan maps depicting "appropriate locations with high potential for renewable energy production with minimal potential for conflicts with other existing uses or sensitive environments" and a framework for coordinating timely local and state agency review of proposed marine renewable energy projects while considering impacts to the environment and existing uses.[1]

Washington State's CMSP planning process is occurring after a similar planning process took place in Oregon. Between 2008 and 2012, Oregon agencies and stakeholders worked through a Governor-directed process to amend the existing Territorial Sea Plan to guide the siting of marine renewable energy projects in Oregon waters. In 2009, state policies, guidance, and procedures to be used to govern marine energy projects were approved. The next phase of this work was spatial mapping of marine activities including areas for potential renewable energy development. Driven by Oregon's Statewide Planning Goal 19, which aims to protect existing ocean uses, siting requirements for likely renewable energy generation technologies were not considered until late in the planning process. This resulted in preliminary maps that limited development to sites that were not economic, realistic, or suitable for marine renewable energy. The state has since worked with the ocean renewable energy industry to include data on renewable energy suitability; this has led to consideration of sites that meet renewable energy needs while also reducing effects on other use groups and resulted in an amendment to the state's existing Territorial Sea Plan in January of 2013 to include sites for renewable ocean energy off Oregon's coast (Geerlofs et al. 2011).

Identifying *appropriate locations with high potential for renewable energy production* on the Washington coast requires an understanding of the conditions necessary to support that use so that suitability can realistically be considered against the backdrop of existing uses and constraints. Geospatial analyses have been used elsewhere to identify the most suitable areas for renewable energy facilities (e.g., Dhanju et. al 2008, Nobre et al. 2009). Spatial multi-criteria decision analyses (MCDA), such as this study (Malczewski 1999) are useful to objectively examine and weigh multiple considerations over a study area, identifying those that maximize or optimize criteria. This geospatial multi-criteria decision analysis expands on the methods used in the cumulative effects analysis for the Oregon coast (OWET 2010) and adapts the approach to Washington State, including tidal and offshore wind energy as well as wave energy. In this study, we use a series of geospatial models to identify areas of potential suitability for marine renewable energy.

At this time, there are no marine renewable energy projects proposed off Washington's coast and, to the best of our knowledge, coast-wide development feasibility has not been evaluated, although

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[1] See Substitute Senate Bill 6350, 2010, for the specific language directing this work, especially Section 6(4).

Hagerman et al. (2004) conducted a wave energy analysis of four sites on the Washington coast. Considering this planning need and the nascent state of the industry, Washington State Department of Natural Resources (DNR) requested this spatial analysis early in the CMSP process to evaluate the most fundamental aspects of feasibility. This study delivers relevant geospatial data and analysis to DNR, other state agencies, and the Washington Coastal Marine Advisory Committee (WCMAC) charged with consideration of ocean renewable energy in the context of all existing and future ocean uses.

1.1 Study Purpose and Scope

The purpose of this project is to inform ongoing marine spatial planning with information about the most feasible places to develop tidal, wave, and offshore wind energy considering technical and economic parameters. Legal, regulatory, socioeconomic, and environmental factors are beyond the scope of this study.

As part of Washington State's ongoing CMSP process, the state is currently working with coastal stakeholders to define the spatial and temporal planning horizon for ocean and coastal uses covered under the Marine Spatial Plan. We focused this study on marine renewable energy technologies suitable for development off Washington's coast and that could be used in a project commencing in a planning or feasibility phase within the next five to seven years. This time horizon serves to narrow the focus on existing, tested technologies deployed within a few miles of shore, with the exception of offshore wind floating platform technology which we assume would be feasible to deploy within 20 miles of shore.

2 Methods

This study used a MCDA framework of weighted additive algorithms to evaluate site suitability. Three multi-dimensional siting factors were considered:

- **Site Quality**: How good is the site in terms of energy resource potential and meeting basic technical needs of the device?
- **Grid Connection**: What is the site's location relative to available electrical transmission and distribution infrastructure?
- **Shore-Side Support:** How close is the site to necessary port infrastructure for device installation, operation, maintenance, and decommissioning?

2.1 Study Area

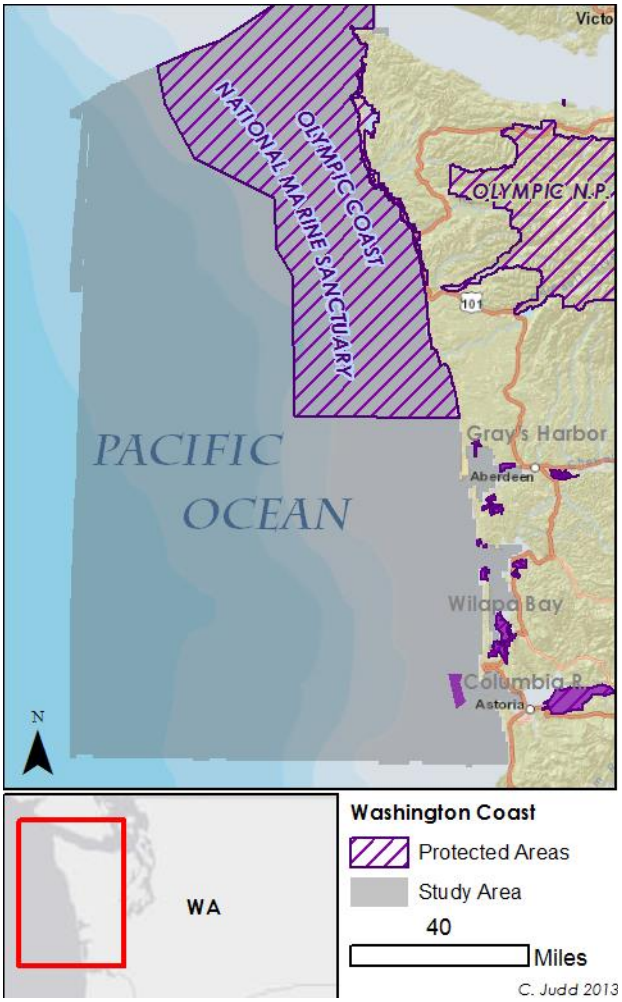

Figure 1. Suitability Analysis Study Area

Our study area extended from the Pacific shoreline of the Washington coast west to the outer limit of Bureau of Ocean Energy Management’s (BOEM), Outer Continental Shelf (OCS) Lease Blocks. It is bound to the north by Cape Flattery at the entrance to the Strait of Juan de Fuca and the Territorial Boundary with Canada, and to the south, by the Columbia River. The Strait of Juan de Fuca and the Puget Sound are not included in the marine spatial planning activities currently underway in Washington and are therefore excluded from our study area.

The Washington coast can be characterized as mostly rural, culturally distinct from the rest of the state, and sustained by a natural resource-based and increasingly tourism-based economy. Coastal shipping and marine transportation; U.S. Navy training exercises; and finfish and shellfish harvesting, both recreational and commercial, are major uses of coastal waters. Recreation and tourism are also important activities on the shore and in nearshore waters.

Four treaty tribes have reservations on the northern portion of the Washington coast and their treaty-protected Usual and Accustomed fishing areas occupy much of Washington’s coastal waters. A prominent feature is the Olympic Coast National Marine Sanctuary (OCNMS), which occupies roughly the northern half of the coast (135 miles or 217 kilometers) and extends seaward between 25 to 40 miles (40 to 64 km) (Figure 1). The OCNMS joins the Olympic National Park at the mean high water line for 48 miles (77 km). Several other federal, state, or local areas of special marine protection occupy the coast. The Olympic National Park and Olympic National Forest occupy significant portions of Clallam and Jefferson Counties. In addition, the U.S. Navy uses an area off the Jefferson County coastline for operations and training (Bedard and Previsic 2014).

The southern portion of the Washington coast is more populated than the north coast, with more urbanized areas, industry, and public infrastructure (e.g., roads, rail, and electrical grid). Electricity is supplied to residents in the four coastal counties by Public Utility Districts (PUDs) in Clallam, Grays Harbor, and Pacific Counties. Jefferson County residents in the area are served by Clallam and Grays Harbor PUDs.

2.2 Technology and Device Selection

We developed eight models to represent existing and relevant ocean energy technologies[2]. Additional information on the ocean energy technologies included in our analysis can be found in Appendix A. The devices we selected to represent wave, tidal, and offshore wind technologies are believed to represent the core device types anticipated to be commercially-viable in the Pacific Northwest. While there are currently multiple devices used to capture ocean energy, it is often the case that basic device requirements are similar with respect to operating conditions. Therefore, we were able to represent multiple devices together in models, allowing us to represent a broad suite of developer perspectives and a range of technologies (Table 1).

Table 1. Eight Models Used to Evaluate Suitability for Renewable Marine Energy Technologies

Technology	Device Type	
Offshore wind	**1. Floating platform**	
	2. Monopile	**Fixed foundation**
	3. Tripod/Jacket	
Wave	**4. Nearshore general**	**Nearshore device**
	5. M3-specific[a]	
	6. Mid-water	
	7. Deepwater	
Tidal	**8. Horizontal and vertical axis**	

[a] *In the case of three likely nearshore wave energy devices, differences among devices were too great to capture suitability in one model. Therefore, suitability of the M3 device is considered separately from the other two nearshore wave energy devices.*

For example, three distinct wave energy device suitability models were developed based on similar requirements for technology classes: nearshore, mid-depth, and deepwater wave energy device feasibility models. Available technologies drove the development of models, and in all but one case (M3), the models are designed to reflect more than one specific device.

- **The Nearshore Wave Energy Device Feasibility** data layer reflects technology constraints for coastline converter and near-shore surge wave energy device types. Coastline converter devices are located on an existing natural or man-made coastline, or where a new coastline is artificially created in nearshore waters. Coastal surge devices harness the energy generated by a flap moving laterally in response to wave motion in shallow water.
- **The Mid-Depth Wave Energy Device Feasibility** data layer reflects technology constraints for mid-depth devices, including oscillating water column, offshore pressure devices, and mid-depth surge devices operating in depths ranging from 10 m to 50 m (5.5 to 27.3 fathoms). Mid-depth

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[2] Offshore wind, wave, and tidal energy generation methods are referred to here as marine renewable energy “technologies”. The term “device” is used here to describe the actual mechanism for capturing energy and could refer to a trade name (e.g., PowerBuoy) or a class of devices (e.g., oscillating water column).

offshore oscillating water column devices generate energy via an above-surface turbine powered by the surge generated by waves within a below-surface chamber. Mid-depth offshore pressure devices generate energy via a seabed-based flexible reservoir that cyclically compresses and expands as wave peaks and troughs pass over. Mid-depth offshore surge devices generate energy via the pressure differential created by two proximal arms moved by passing waves.

- **The Deepwater Wave Energy Device Feasibility** data layer reflects technology constraints for deepwater wave energy devices that are often anchored at depths of 50 m to 125 m (27.3 to 68.4 fathoms), including point absorber, oscillating water column, offshore surge, and attenuator and pivot device types. Point absorber wave energy devices contain floating structures that absorb energy in all directions through its movements at or near the water surface. Deepwater offshore oscillating water column wave energy devices capture the surge generated by waves within a chamber that is used to drive air through an above-surface turbine. Deepwater offshore surge devices generate energy via the pressure differential created by two proximal arms moved by passing waves. Attenuator or pivot wave energy devices capture the energy of passing waves via of the resistance of an articulated joint that is moved around a pivot to generate electricity. Similarly, distinctions between offshore wind devices necessitated the differentiation between devices mounted on floating platforms, tripod or jacket foundations, and monopile foundations.

We considered full-scale devices/turbines technologically mature enough to be candidates for development in the Washington coast environment in the near future. The marine renewable energy industry is still very young due to limited deployment experience.[3] Therefore, marine renewable energy projects in the United States are largely being developed as pre-commercial or demonstration projects, the primary purpose of which is to test and validate new or innovative uses of technology of combinations of technologies. A demonstration project may have numerous objectives, including:

1. Developing and validating engineering and technical aspects of devices and demonstration of commercial potential.

2. Developing an understanding of the environmental effects of devices and their potential impacts on other uses or users of the marine area through monitoring and research.

3. Evolving and refining of the regulatory process and adaptation as appropriate to new technologies and their effects.

Although all three marine renewable energy technologies are considered to be in a pre-commercial stage currently, we consider wave and tidal energy technologies to be operating in an economically-constrained environment while offshore wind technologies are not. In economically-constrained conditions, wave and tidal energy devices do not generate significant electricity or revenue, and as a result, the suitability scores reflect the financial importance of proximity to shore and a potential grid connection. In contrast, due to a significantly more energetic resource and more mature technologies, we did not consider offshore wind technology to be economically-constrained.

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[3] The device technology, distinct from the industry as a whole, is also in early stages for wave and tidal, but not for wind turbines due to a legacy of deployment on land.

2.3 Geospatial Assessment

We developed eight separate spatial algorithms as part of a MCDA framework to characterize site suitability, one for each of the eight device types shown in Table 1. To do so, we followed a five step process:

1. Develop conceptual models to describe factors (i.e., potential "attributes") relevant to siting and operating selected devices.

2. Review of draft conceptual models and attributes by industry advisors.

3. Select geospatial data to represent attributes in the conceptual model and develop geospatial database.

4. Weight sub-models and attributes based on advisor feedback and assign relative scores to gradations of each attribute.

5. Examine uncertainty and model sensitivity.

The analysis resulted in eight suitability maps for the Washington coastal area as well as a geospatial dataset.

2.3.1 Development of Conceptual Models and Feasibility Attributes

Conceptual models document our understanding of the important factors and processes that contribute to a spatial pattern (Burroughs and McDonnel 1998). They can be particularly useful when developing geospatial models with stakeholders and help clarify conceptual differences (e.g., Harvey 1997). We developed a conceptual model for each device type examined, building off the models developed in OWET (2010) (Appendix C).

Each model for site suitability is comprised of three sub-models, which is in turn described by two or three attributes (Figure 2).

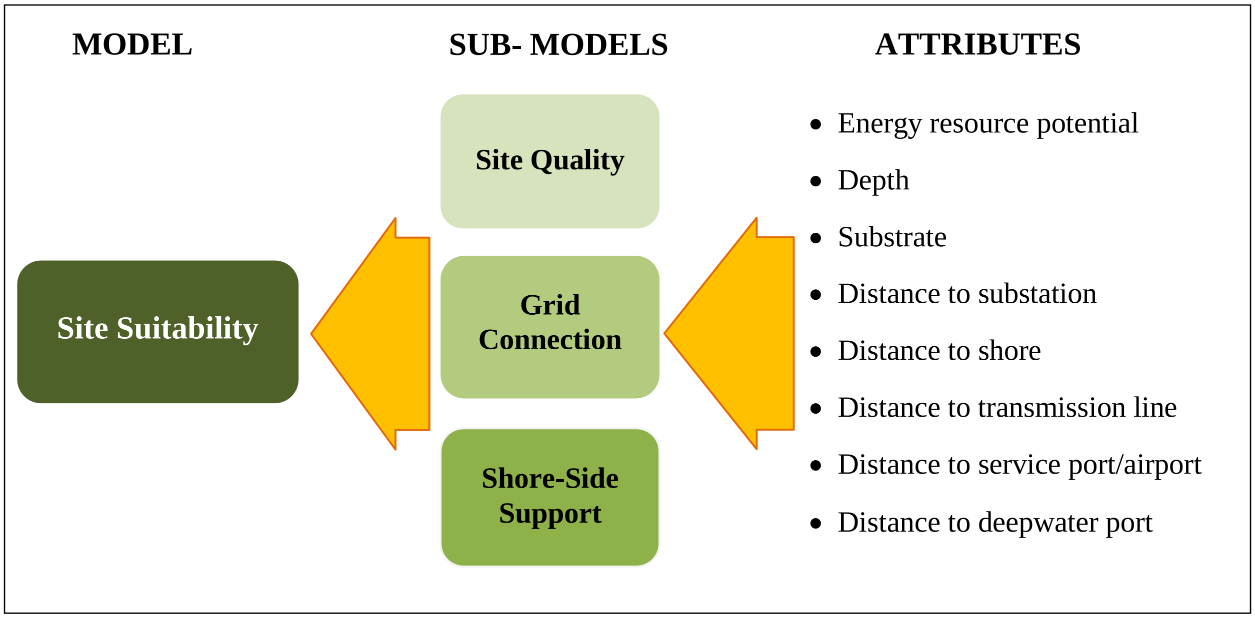

Figure 2. General Model Framework
Site suitability is described by three sub-models, which in turn are described by attributes.

Attributes used to describe site suitability are based on OWET 2010 and were refined to reflect technical and economic considerations for offshore wind and tidal energy (Table 2). The depth and the infrastructure generally associated with ports meet the needs of most tidal and wave devices examined in this study. Ports with channel depths greater than 30 feet are generally considered to be "deepwater ports." The scale of offshore wind turbines and challenges associated with transporting and handling turbines up to 500 feet tall require greater specificity in defining deepwater port with capacity to support offshore wind development.

Table 2. Attribute Definitions

Attribute	Description
Energy resource potential	Measure of mean energy potential as wind speed or mean power density.
Depth	Depth from water surface to seabed.
Substrate	Type of sediment on the surface of the seabed.
Distance to Substation	Euclidean distance† from site to the nearest substation.
Distance to Shore	Euclidean distance from the site to the coast.
Distance to Transmission Line	Euclidean distance from nearest shore access point to the nearest transmission line.
Distance to Service Port /Airport	Euclidean distance from the site to nearest port or airport.*
Distance to Deepwater Port	Euclidean distance from the site to nearest deepwater port.**

† Distance was calculated using Euclidean or straight line distance. It is a simpler but more straightforward method than calculating the route distance.

* Service port is defined by the U.S. Army Corps of Engineers (see Appendix B). Banister (2013) reported that maintenance activities on offshore wind floating platforms would likely be performed by helicopter; therefore, in the offshore wind floating platform model only, distance to nearest airport is measured rather than distance to service port.

** Deepwater ports are generally considered ports with channel depths of at least 30 feet. However, in the case of offshore wind technologies, additional overhead clearance requirements further narrowed the list of adequate deepwater ports.

In their analysis of port infrastructure needs for offshore wind energy development, Tetra Tech identified first tier criteria relative to harbor access and second tier criteria relative to port facilities (Tetra Tech 2010). Although an in-depth analysis of Washington port capacity was not within the scope of this study, we conducted a cursory analysis of eight nearby Washington ports against these criteria using the Pacific Northwest Ports Handbook (Marine Exchange of Puget Sound 2012), other web-based resources[4], and individual port websites. As a result, *distance to deepwater* port was measured from one of three nearest ports, Astoria, Grays Harbor, and Port Angeles, although the Port of Port Angeles may lack sufficient yard space and rail access. Other, more distant ports in the region met the infrastructure needs criteria. Only the Port of Vancouver was eliminated due to insufficient overhead clearance between the port and a potential offshore site.

2.3.2 Review by Industry Advisors

In order to ensure the study results accurately reflect technical and basic economic siting decisions, industry experts – device developers, project developers, industry coalitions, or academic experts – were asked to participate in model development, selection of attributes, and scoring of attributes. Twenty companies or organizations were contacted; ten provided feedback. The companies/organizations and the technology type on which they provided feedback are presented in Table 3.

Table 3. Companies or Organizations Providing Advice on Specific Technologies and Device Type Models

Technology		**Device Type**	**Industry Advisor**
Offshore Wind	(1) Floating Platform	WindFloat	Principle Power
	Fixed Foundation *(two models)*	(2) Monopile	Offshore Development Coalition
		(3) Jacket/Tripod	
Wave	Nearshore Wave *(two models)*	(4) Oyster	Aquamarine
		(4) SurgeWEC[a]	Resolute Marine Energy
		(5) M3 Delos-Reyes Marrow	M3 Wave Energy Systems, LLC
	(6) Mid-Depth Wave	Rotating Mass Turbine WEC	Neptune Wave Power , LLC
	(7) Deepwater Wave	StingRAY	Columbia Power Technologies, LLC
		PowerBuoy	Ocean Power Technologies, Inc.
	All wave	All	Northwest Energy Innovations/ Pacific Energy Ventures
			NNMREC[b]/Oregon State University
Tidal	(8) Tidal	Turbine Generator Unit (TGU)	Ocean Renewable Power Company, LLC
		All	NNMREC[b]/University of Washington

Numbers indicates the eight device types modeled.

[a] *Wave Energy Converter*

[b] *Northwest National Marine Renewable Energy Center*

Industry advisors were contacted in March 2013. Each advisor was provided draft conceptual models and asked to comment on the following: (a) if the correct sub-models were identified, (b) if the correct

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[4] Other web-based resources used include: Wells and McConnell 2011, Nova Scotia Department of Energy 2011, and Lindblom 2012.

attributes associated with each sub-model were identified, (c) the relative importance or ranking of each sub-model to predict suitability, and (d) if scoring for each attribute reflected known specifications or requirements for anchoring and operating the marine renewable devices. Advisors directed many changes and adjustments to attributes, scores, and weights, and their valuable feedback was incorporated into the study.

Advisors were introduced to the study via webinar presentation. Acknowledging the competitive nature of the industry while also encouraging participation, individual, follow-up interviews were scheduled with participants to collect in-depth feedback.

Select advisors were engaged to develop weighting factors in some cases. Following revisions based on feedback, industry advisors were contacted in May 2013 for final review of weighted models and attribute scores.

2.3.3 Development of Geospatial Database

We developed a geospatial database for the Washington coast, based on BOEM's OCS leasing blocks. The dataset divides each of the blocks into sixteen, 1.44 square kilometer sections (0.56 mi^2), for a total of 24,291 units (aliquots). These are the minimum units for this analysis, and what are referred to as "sites" within this report. The original BOEM OCS dataset did not include blocks within 3 nautical miles (nm) of the shoreline. Hence, to provide complete coverage, nearshore blocks were digitized and included to provide a full coverage of the area of interest (Figure 3). Based on the conceptual models reviewed by industry advisors, we added attributes to the geodatabase to record:

- Minimum and maximum site depth.
- Bottom sediment type.
- Energy resource potential (wind, wave and tidal).
- Distance to shore, transmission lines, substations, ports, and airports.

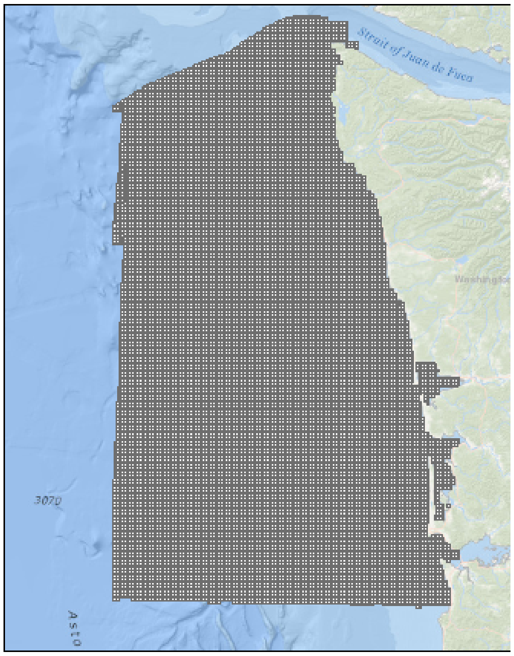

Figure 3. Sites from Geospatial Database
New sites were added to database to provide coverage within coastal and nearshore areas.

Data sources used were readily available through national and state geospatial datasets. A description of these attributes and data sources can be found in Appendix B. For individual siting assessments, additional geospatial data would help inform siting. For example, in one instance, an industry advisor identified the presence of quay side space and lay down areas adjacent to the installation site as critically important, more important in fact than proximity to port facilities (Murray 2013). Although this shoreline information is not currently available, it could be compiled to support siting analyses in specific areas. Site slope and roughness were two other important basic siting factors that were noted (Lesemann 2013). We found that the resolution of this coast-wide analysis is too coarse to meaningfully include these metrics, but incorporation of higher resolution bathymetry for individual siting assessments may be very helpful.

2.3.4 Development of Scores and Weights

Following industry advisor input, we developed eight algorithms to describe the relative suitability of sites for each device type. This involved the development of both the final site suitability model, as well as the development of sub-models to represent each of the three main factors (site quality, grid connection, and shore side-support), which in turn, were informed by the attributes of importance at each site (Figure 4). Appendix C contains the eight final conceptual models and associated scored attribute tables.

In order to represent differences in suitability within each attribute, we developed and scored attribute classes based on industry feedback. Scores for attributes range from 0 to 10, with 0 representing no potential for development and 10 representing conditions that are favorable for development.

In addition to receiving input on suitability ranges for each attribute, industry advisors provided feedback that some sub-models were more important for suitability considerations than others. Prior modeling (OWET 2010) included no weights for sub-models; all models and attributes were weighted equally. However, in response to industry recommendations, we applied weights at the sub-model level as illustrated in the example model (Figure 4).

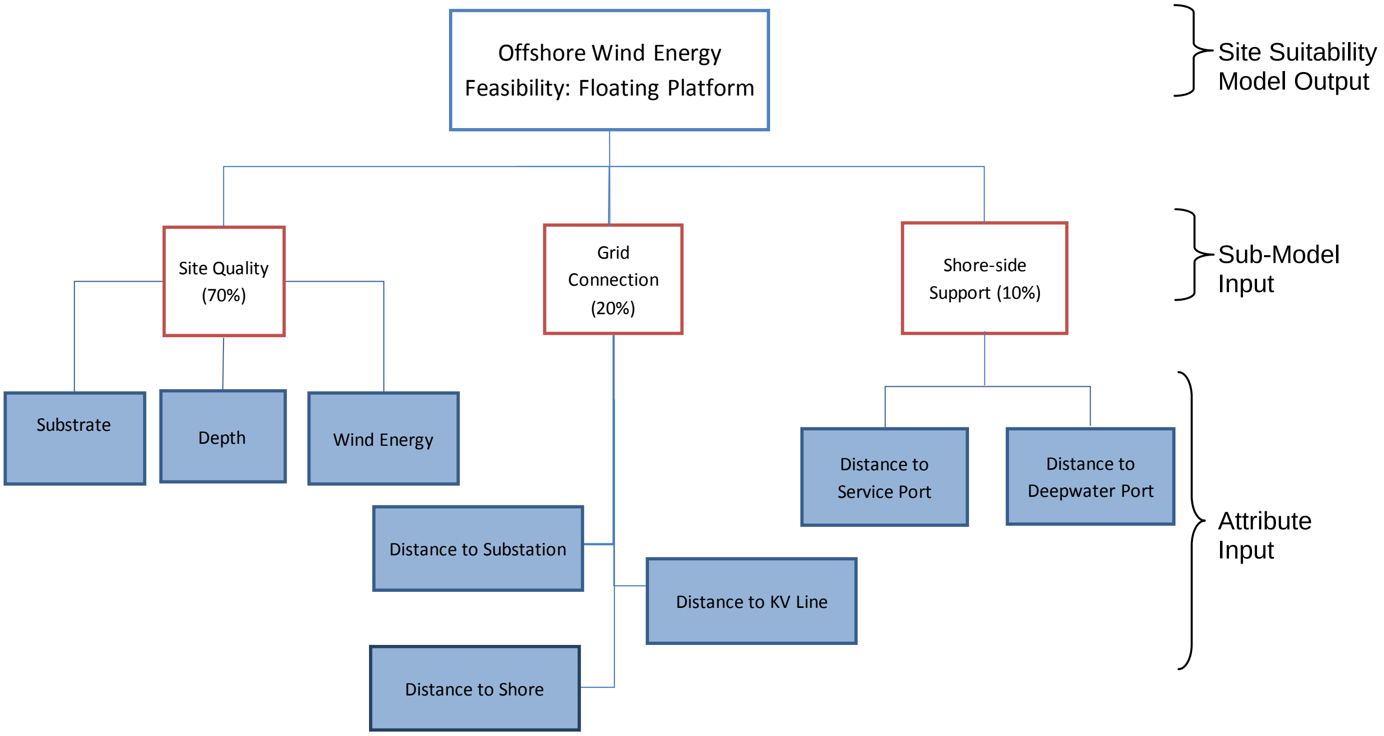

Figure 4. Conceptual Model Example: Offshore Wind Floating Platform Model
This model shows model components and an example of how weighting (see percentages shown) was applied to sub-models. Attribute scores (blue boxes) are input into sub-models (boxes with red outline) where weighting is applied. Weighted sub-model inputs are used to derive model-level suitability (boxes with blue outline).

Sub-models develop and score a factor of importance for the site suitability model. The output of each is a score between 0.0 and 1.0 for each device type, describing (a) the site quality for the site, (b) grid connection, and (c) shore-side support for the particular device type. Each is evaluated through a weighted additive model where:

$$Sub\text{-}Model\ Score = \frac{\sum_{k=0}^{n}(Attribute\ \ Score\ ) \times Weig\,ht}{Potential\ \ Maximum\ \ Score}$$ k=0 indicates lower limit, n=upper limit

Unless recommended by industry and technical experts, each attribute was considered of equal importance (i.e., weight =1) for the sub-model characterization. The following attribute scores were included:

- **Site quality sub-model** is comprised of attribute scores for (1) energy resource, (2) site water depth, and (3) substrate composition.
- **Grid connection sub-model** includes attribute scores for (1) the distance from the project site to shore (proxy for underground cable route), (2) the distance from shore to the nearest transmission line, and (3) the distance from shore to the nearest substation.
- **Shore-side support sub-model** includes attributes for (1) distance to the nearest acceptable deepwater port for device deployment and recovery, and (2) distance to the nearest service port (or airport, in the case of the floating platform) for periodic maintenance activities.

The final site suitability algorithm considers all three sub-model scores, where, w = weight of factor for each device type ($_a$):

$$Site\ Suitability_a = \frac{(w_{1a} \times Site\ Quality\ + w_{2a} \times Grid\ Connection + w_{3a} \times Shore - Side\ Support)}{Potential\ Maximum\ Score_a}$$

The final site suitability score ranged from 0.0 to 1.0 for the device type. Any site not meeting resource or device needs was assigned a score of 0.

2.3.4.1 Processing and Data Visualization

Site suitability models were run in ArcGIS 10.0, using a series of Python scripts to calculate attribute scores, apply sub-model weights, and determine raw suitability scoring for each model in one geodatabase. In order to make the suitability scores more visually understandable, we classified the relative suitability scores from least to greatest into ten equal groups (i.e., deciles) for each device type. Thus, each of the 24,291 sites had a suitability score between 0.0 and 1.0, representing actual suitability, and a decile score summarizing relative suitability as compared with other sites in the study area. To map the study results, the decile score was used to visualize these groups of suitability scores. For example, the top decile (i.e., the 90th percentile or the top 10 percent) is represented on the device type suitability maps in red, the 80th percentile is represented in orange, etc.

According to this approach, all sites meeting minimum suitability criteria are considered, and those that did not were eliminated. However, in order to focus on the most suitable areas off the Washington coast and lacking an externally enforced hard cut-off between “more suitable” and “less suitable,” we elected to focus our discussion of results on the top 30 percent most suitable sites.

2.3.5 Sensitivity and Uncertainty Assessment

As part of the model creation process, we examined scoring sensitivity and model choices on the final mapped product prior to selection of the weighted additive algorithm. Prior projects for assessing renewable energy had used MCDA approaches (Wang et al. 2009); however, there are many different algorithms that can be potentially used. As we were using scores derived from industry advisor input, we wanted the process and scoring to be as straightforward as possible. Similar assessments have used a weighted product model; however, the weighted additive model is the more popular approach due to its ease of application and transparency (Wang et al. 2009).

Another important consideration stemmed from utilizing scores for different attributes based on industry advisor input. We were concerned about how uncertainty in assigning scores might impact the final product. For example, when evaluating how suitable a substrate of *sand* is over *cobbles*, knowing that *sand* is better for a particular device, which scores should be assigned to reflect this preference: 5 and 8? 6 and 7? Or 4 and 10? While there are formal methods of scoring (e.g., Pairwise comparison), we used input from well-informed but non-technical advisors and evaluated methodological tradeoffs considering the high value we placed on accessibility and understandability to stakeholders.

Our final consideration was the role of sensitivity of the scoring scheme itself. Steele et al. (2008) emphasized that selection among MCDA methods should include a sensitivity analysis of the scales used to score the individual criteria. This can be accomplished by reducing the scale to three possible scores (low, moderate, high, for example) from a finer resolution scale to assess the consistency (e.g., ranking) of results. Further, the variability of results that are close spatially can also be used to compare MCDA methods (Ligmann-Zielinska and Jankowski 2008). Minor deviations in input should produce minimal variability in the results.

To resolve the considerations described above, we chose one representative device type from each technology (wave, wind, tidal) and examined:

1. **What if we used a different model algorithm?** What would be the impact of two alternative models, a weighted product model and a weighted additive model, on the outcome? We examined how many sites were categorized in a different decile group (Figure 4).
2. **How sensitive is each model to the scoring?** We reduced scoring from 0 to 10 for the attributes to 0 to 3 (none, low, medium and high), comparing how the changes in rankings impacted the final maps.
3. **What is the trajectory of change for minor changes in scoring?** We evaluated how changes in attribute scores by one would impact the final outcome.

We looked at how site scores for the top 30th percentile changed. In both the additive and product modes, the difference in area between the algorithms was greater than the difference in area achieved by condensing the scoring (Table 4).

Table 4. Assessing Sensitivity for Scoring and Algorithms by Device Type

Device Type	No. of Sites Considered for Technology	Total Area (mi^2)	Site Difference Between Algorithms	Sensitivity - Difference in Area (Additive)	Sensitivity - Difference in Area (Product)
Deepwater - Wave	17,693	9,837	18.1%	17.1%	11.6%
Monopile - Wind	2,427	1,349	24.5%	1.8%	1.8%
Tidal	11	4	0%	0%	0%

In this table, Site Difference Between Algorithms represents how many of the sites changed deciles with an additive vs. product algorithm. The two sensitivity columns represent how much area classified in the top 30 percent changed using a simplified scoring algorithm. A robust model should show little sensitivity to change.

Overall, there were differences in area between the different algorithms; these changes were most often evident towards the edge of the suitable zone (Figure 5). The product model seemed more sensitive to changes in rankings than the additive algorithm, and thus would be more likely to be impacted by uncertainty in scoring. However, only three of the eight devices were examined. The difference between the two algorithms (additive vs. product) for the devices examined was greater than the difference in expanded vs. reduced scoring.

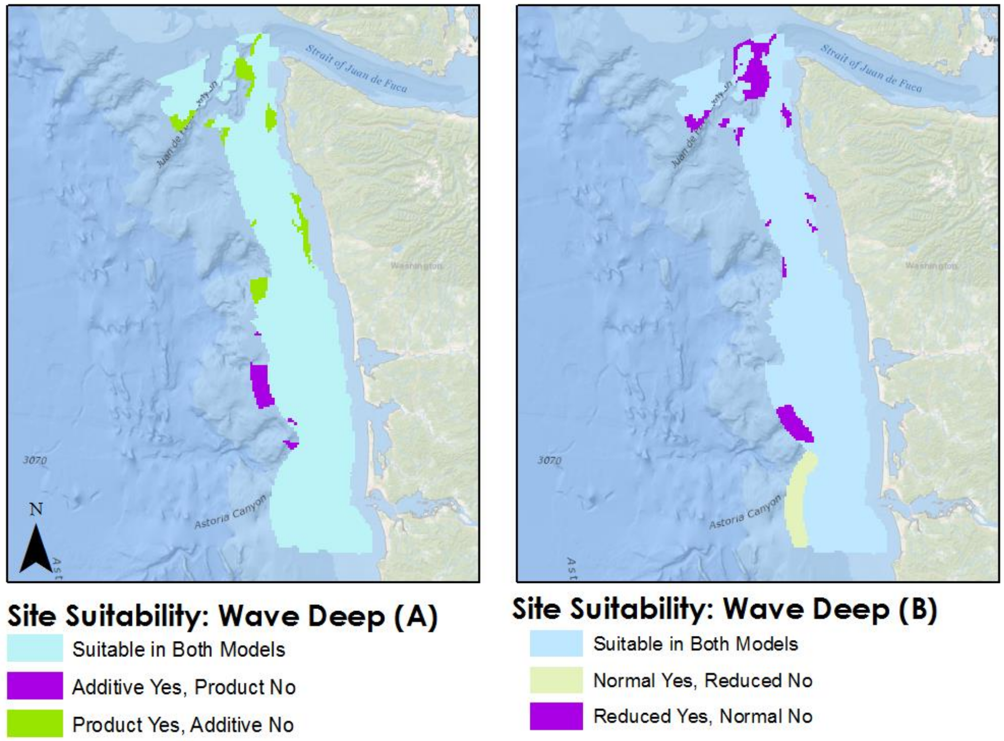

Figure 5. Comparison of Deepwater Wave Device Suitability Derived with Additive v. Product Models. In (A) differences between the additive and product models are shown. Areas shown in blue are in the top 30 percent of sites regardless of the model. Green are those sites that would be in the top 30 percent of sites in the product model, but not the additive model while purple sites would be in the top 30 percent in the additive model, but not the product model.

Note that most areas of uncertainty occur along the edge of the core blue area. Total difference is about 18 percent of the area. In (B), areas that change between the reduced scoring and normal scoring are mapped.

Finally, the upper and lower thresholds of the input data were used to determine the varying impacts of product models on outcomes. The weighted product based models produce incremental change that differs between the lower and upper classes of the data. For instance, an incremental change from 1 to 2 for the *Distance to Port* variable produces a ~0.01 percent change using the weighed product model, while the same change increment from 10 to 9 at the upper threshold produces a 2.1 percent change in the score. Conversely, the additive models react in a consistent, linear way regardless of whether the attribute is at the upper or lower thresholds.

Though the product model was slightly more robust against changes in scores for the models examined, the additive model is more intuitive in how it reacts to changes in the scores. Given the on-going participation and future use by stakeholders, we concluded that the transparency and ease of understanding provided by the weighted additive model was more valuable than the gain in robustness to sensitivity of scoring provided by the weighted product model.

3 Results

Eight suitability maps were developed, one for each model (see Section 3.1) showing over 4,000 square miles off the Washington coast of potentially suitable areas for offshore wind, wave, or tidal energy (Table 5). Many of these top scoring areas are suitable for more than one device type (Figure 6). As sites not meeting basic suitability for energy resource or depth were eliminated from consideration from that particular model, there are differences in total area between device types seen in Table 5. For example, the monopile device model eliminates all sites with a depth greater than 40 meters (21.9 fathoms) (Figure 8) while the deepwater wave model only considers sites with a depth greater than 30 meters (16.4 fathoms) (Figure 10). Vast offshore areas off Washington's active continental margin extend beyond 40 m deep: therefore, there are more potential areas with suitable depth identified in the deepwater wave device model and area within the top 30 percent than for the monopile device model.

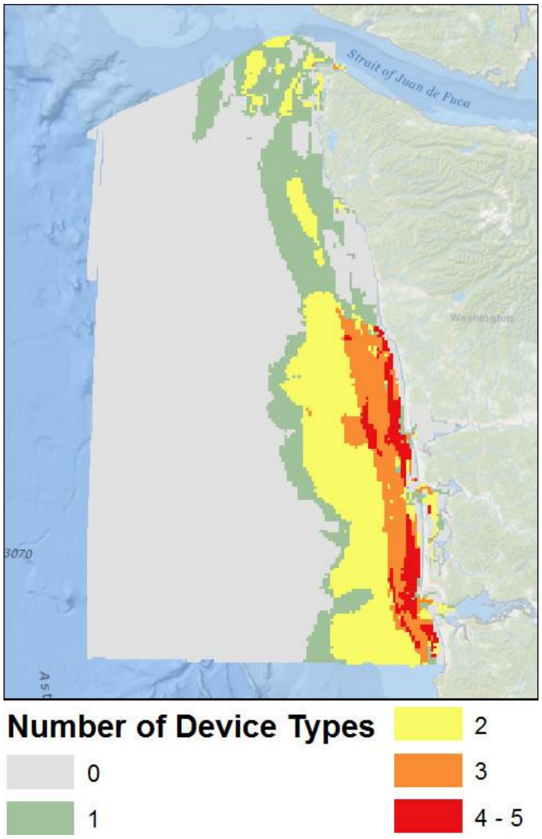

Figure 6. Number of Sub-Technologies in Site Within the Top 30 Percent

Many sites score high in suitability for more than one technology type.

Examining the patterns of distribution in results suggest that there is a wider selection of potential areas in the southern half of the Washington coast that are suitable for marine renewable energy development based on the attributes examined in this analysis. This is especially true for the non-floating wind energy models and the two nearshore wave models (Figures 8, 9, 12, and 13). This difference in suitability between the north and south coasts is present but less distinct in the mid and deepwater models. Given the thresholds used for mean power density, the Washington coast has limited opportunities for tidal energy development. The results suggest there is one suitable area for tidal energy which is located in the mouth of the Columbia River south of Cape Disappointment. Out of 24,291 sites evaluated, only 11 were suitable for tidal energy. In contrast, based on the best available energy resource data, most sites in the study area have suitable energy resources for wave and offshore wind, highlighting the utility of including other basic siting factors in addition to energy resource (as we do in this study).

Most maps in Section 3.1 show a reduction in the suitability of sites between Cape Elizabeth (north of Taholah) and Cape Alava, while offshore of Grays Harbor and Cape Disappointment are areas of high suitability in most maps. The offshore wind floating platform model and all wave models show an increase in suitability near Cape Flattery.

Table 5. Total Area Considered in the Top 30 Percent of Sites for Suitability

Model	**Area (mi^2)**	*Total*
Wind Devices		*3,440*
Floating	2,636	
Jacket/Tripod	788	
Monopile	378	
Wave Devices		*3,557*
Deep	2,946	
Mid	1,100	
Nearshore	119	
Nearshore M3	299	
Tidal Devices[a]	4	

[a] *Since only 11 sites were not eliminated for tidal devices, the top 50 percent were considered (all of these sites had the same score).*

3.1 Suitability Maps

The following maps were produced from this analysis. Each map depicts suitability score by percentile for each device type. Many sites score high in suitability (i.e., top 30 percent) for more than one technology type.

The first three maps show suitability for offshore wind device types (Figures 7, 8, and 9), followed by four maps depicting wave energy suitability (Figures 10, 11, 12, and 13) and one map showing tidal energy suitability (Figure 14). Areas shown in gray did not meet minimum suitability requirements for either site depth or energy resource or both.

The structure of the analysis (i.e., determining a composite suitability score with multiple algorithms factoring in multiple attributes) limits the ability to determine the cause(s) driving suitability percentiles in the maps. Major patterns seen in the following maps are discussed in the next section.

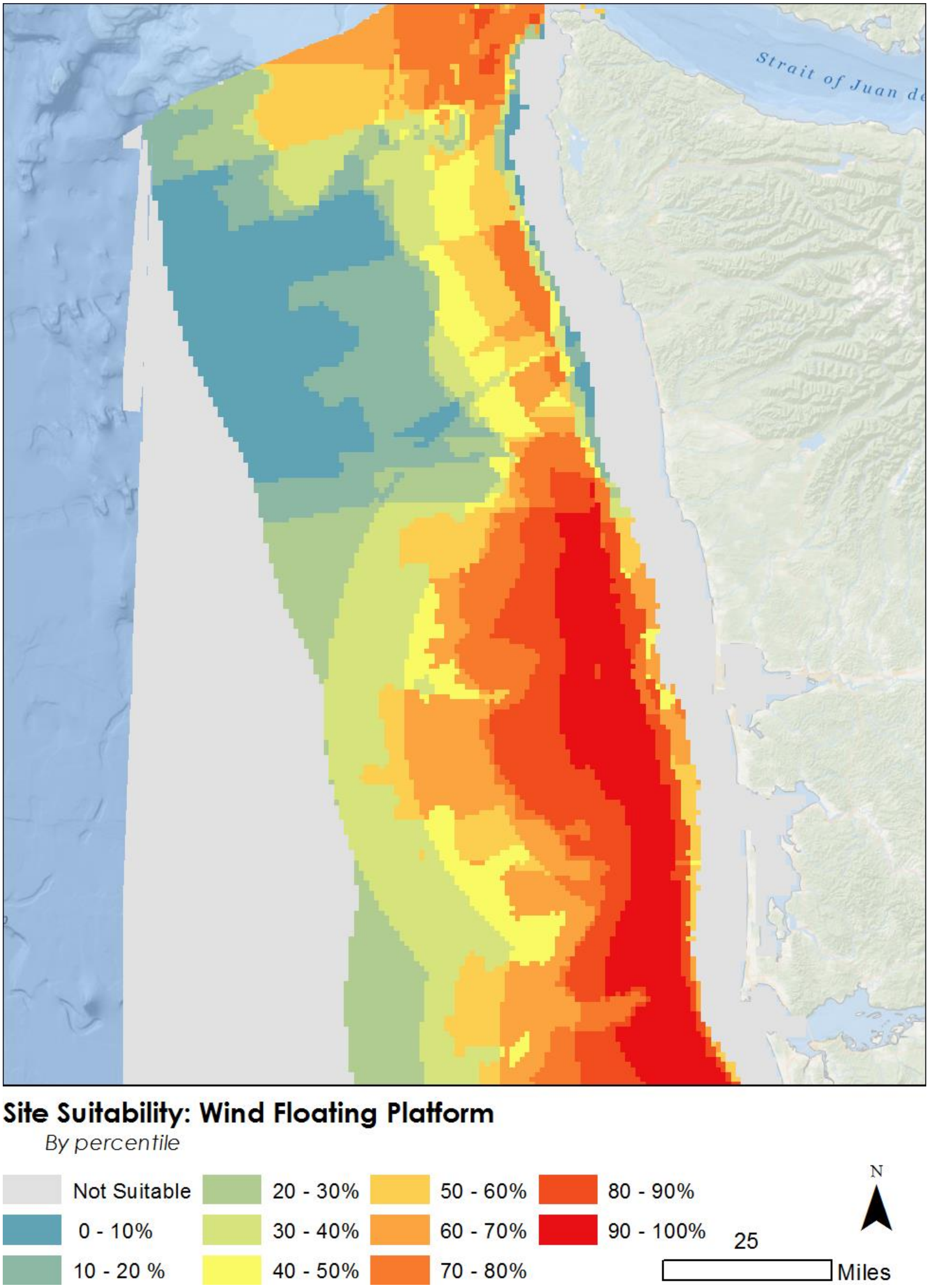

Figure 7. Offshore Wind Energy Suitability – Wind Floating Platform

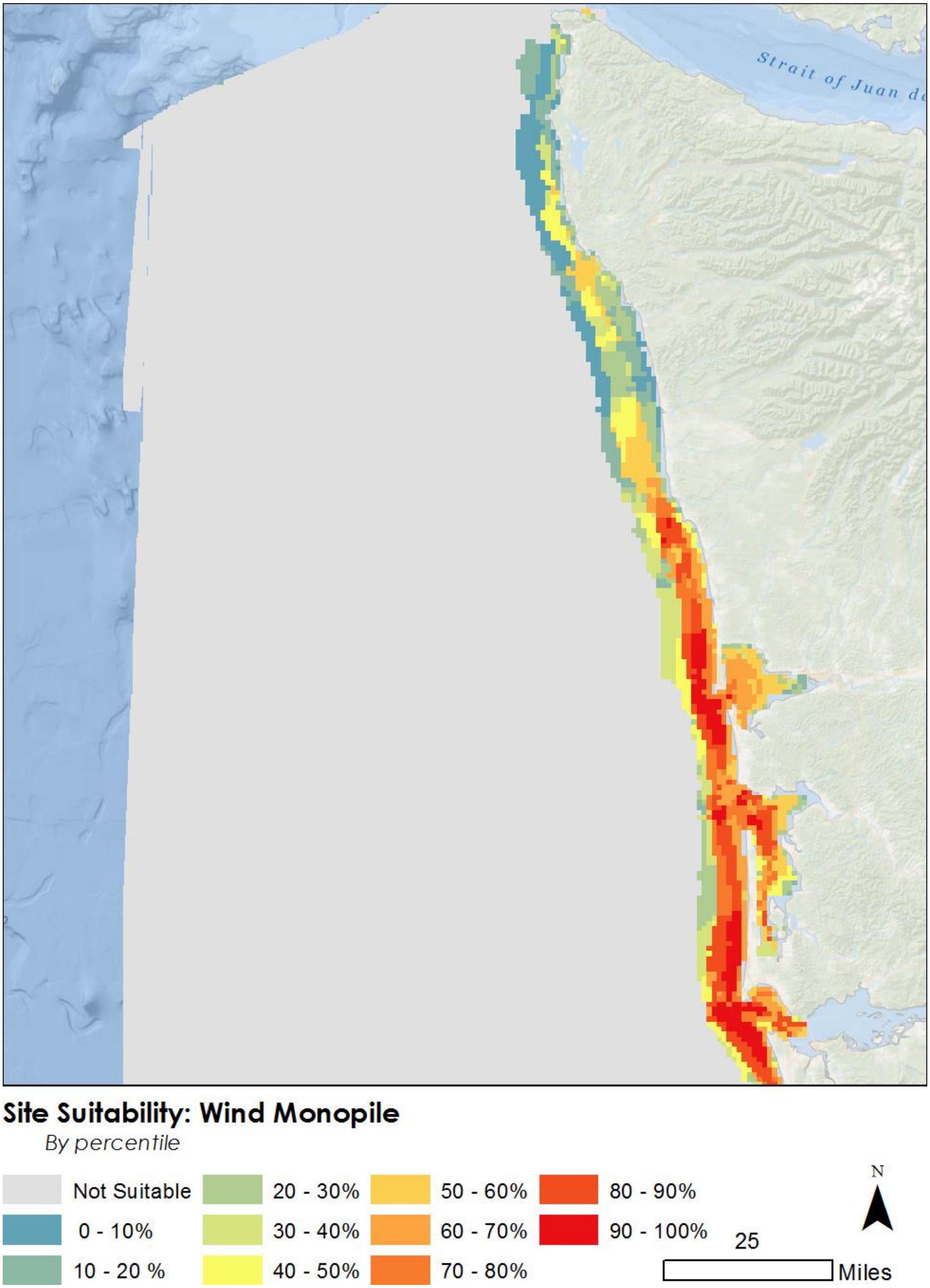

Figure 8. Offshore Wind Energy Suitability – Monopile Foundation

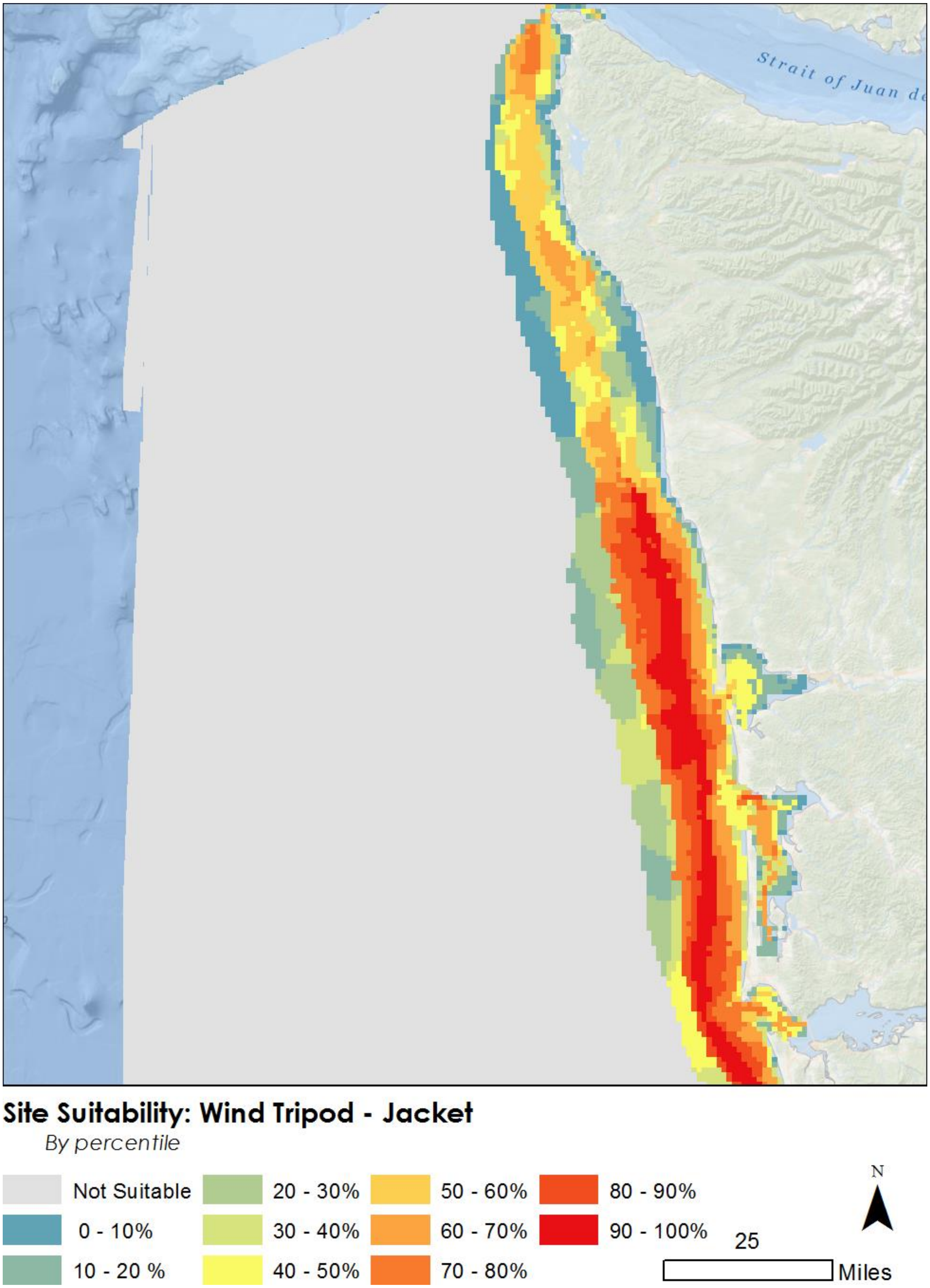

Figure 9. Offshore Wind Energy Suitability – Tripod or Jacket Foundation

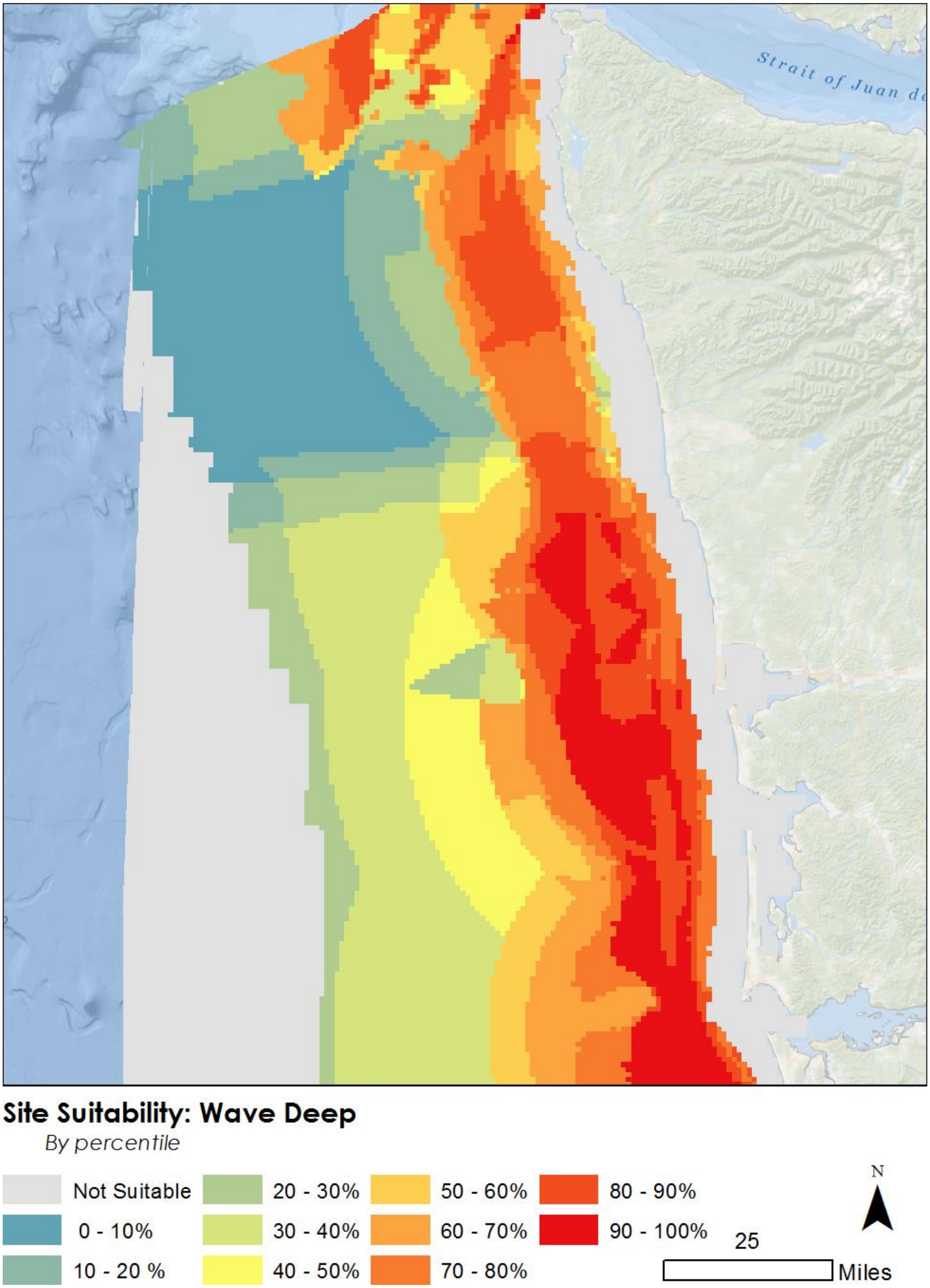

Figure 10. Wave Energy Suitability – Deepwater Devices

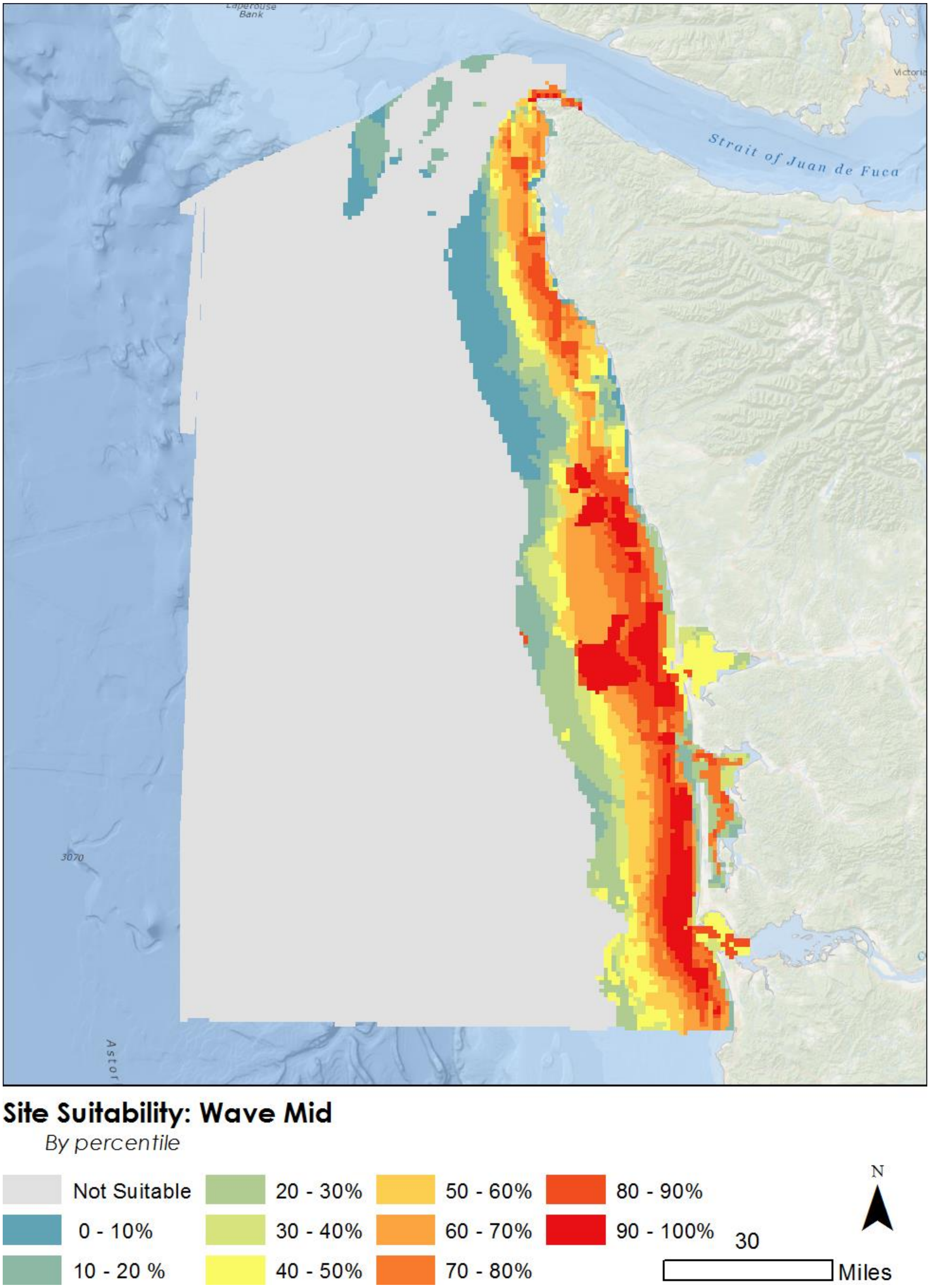

Figure 11. Wave Energy Suitability – Mid-Water Devices

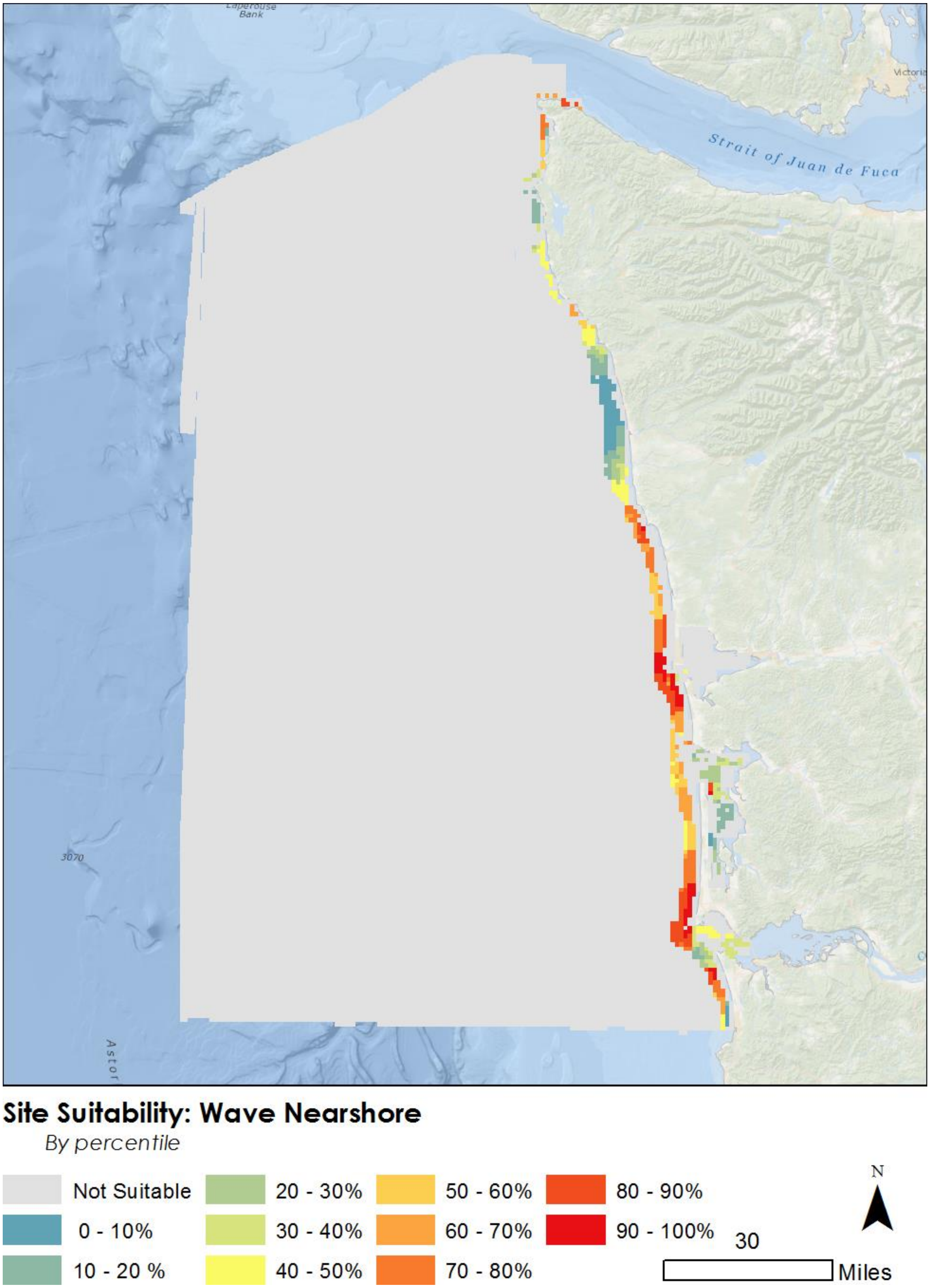

Figure 12. Wave Energy Suitability – Nearshore Devices

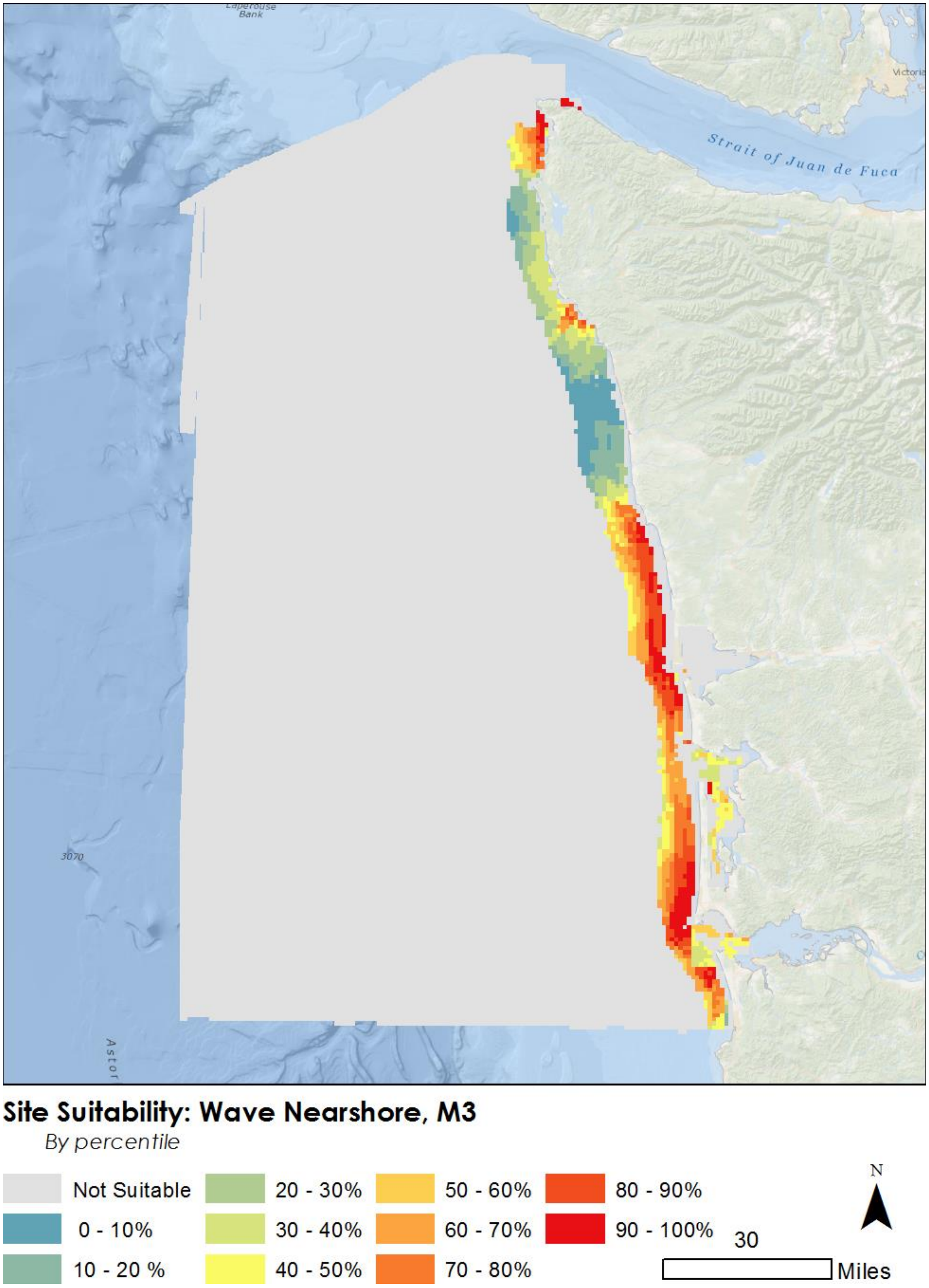

Figure 13. Wave Energy Suitability – Nearshore M3 Device

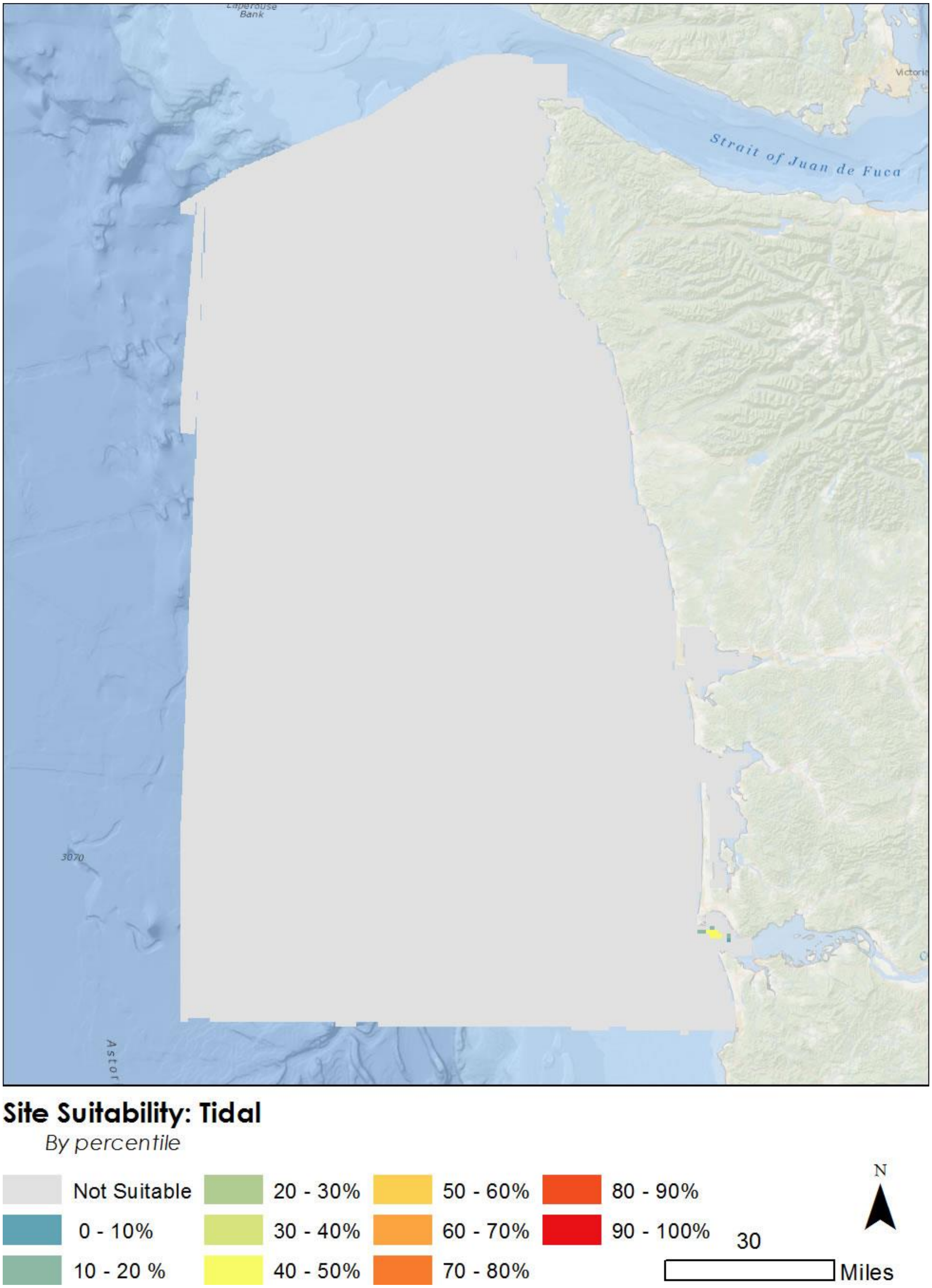

Figure 14. Tidal Energy Suitability

4 Discussion

Our results show a greater number of areas with higher suitability for renewable energy development in the southern half of the Washington coast than the northern half. Many sites are suitable for more than one device type.

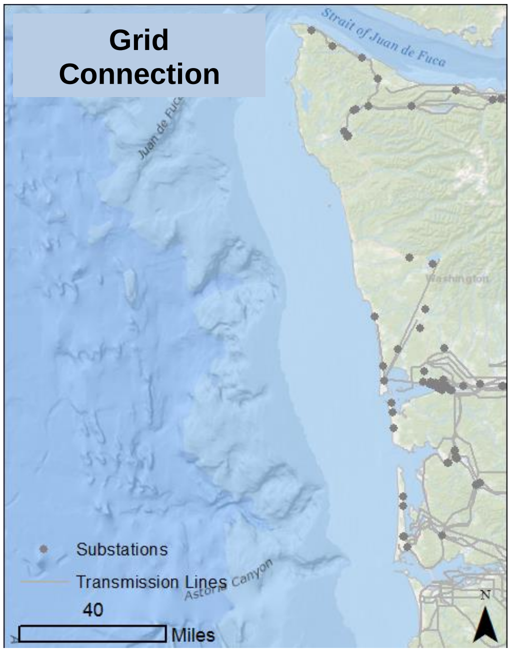

Figure 15. Grid Infrastructure on the Washington Coast

Gaps between transmission line and substations along the northern coast are reflected in final suitability resource maps.

The primary driver of this pattern for wind and wave technologies is grid connectivity, i.e., the lack of supporting electrical infrastructure, including transmission lines and substations along the northern mid-section of the coast (Figure 15). Distance to shoreside support (service ports and deepwater ports) also influences this pattern. As expected, the models that weigh the importance of these sub-models and features higher, exhibit this pattern to a greater degree (e.g., Jacket/Tripod Wind vs. Floating Wind).

Any future expansion of electricity infrastructure in this area would change this pattern and likely expand the suitability of the north coast according to the basic technical and economic attributes used in this study. However, it should also be noted that the Olympic Coast National Marine Sanctuary (OCNMS) also covers much of the northern coast. Within OCNMS boundaries (Figure 1), certain activities are limited or prohibited, including disturbance of the seafloor.[5] While the OCNMS has the authority to grant specific permission to a renewable energy developer to place anchors or install structures on the seafloor, the activity would be highly regulated and needs to be consistent with OCNMS conservation objectives. Further, the Federal Power Act states that the lease-letting agency for wind, BOEM, is explicitly disallowed to grant leases for projects located in a National Marine Sanctuary or National Wildlife Refuge (BOEM/FERC 2012). This effectively limits the potential for offshore wind in the OCNMS. However, it may be possible for FERC to grant a license without a BOEM lease for wave or tidal energy located on the OCS within the OCNMS.

While our results suggest sites within the OCNMS tend to have lower percentile scores and the numbers of highly suitable sites are fewer than south of the OCNMS, there are still suitable areas located within the OCNMS. However, given the increased regulatory process involved in evaluating the appropriateness of siting energy generation structures in a National Marine Sanctuary, it is unlikely a developer would select a site within the OCNMS given other alternatives on the Washington coast or in other states all together. Although, outside the scope of this study, this consideration of the OCNMS provides an illustration of how important consideration of legal (such as Usual and Accustomed fishing areas for Treaty Tribes), national security, regulatory, environmental, and other socioeconomic factors will be in planning for renewable energy on the coast.

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[5] For a complete list of regulations, please see the OCNMS website http://olympiccoast.noaa.gov/protect/regulations/regulations.html.

Devices that can be placed in deep water, such as the floating platform for wind energy and the deepwater wave device, exhibit a greater total potential area for siting (Figures 7 and 10). Much of the offshore coastal area for Washington has deep waters (depths greater than 100 m or 55 fathoms). Those devices that are limited to shallow waters, such as tidal devices or nearshore wave devices, have fewer potential areas for deployment. However, by examining percentiles of sites, rather than actual scores, we limit our ability to compare between devices. For example, sites ranked in the top 30 percent for deepwater wave devices only have a mean score of 0.77, while those for nearshore wave have a mean score of 0.93. Viewing the actual scores versus the relative suitability may change the patterns observed.

Few places were suitable for tidal energy development on Washington's outer coast based on our analysis. This is primarily due to the resource itself. There are few places along the coast that maintain the minimum suitable mean power density of 0.5 kilowatts per square meter (kW/m^2), although there are several marginal areas not considered suitable in this analysis that may prove feasible in the future given emerging technologies capable of operating in lower flow environments (Figure 16). This finding does not apply to locations outside the study area, such as Admiralty Inlet or the Tacoma Narrows in the Puget Sound where significant tidal energy have been documented (Polayge and Previsic 2006, Hamner et al. 2007).

In addition, areas that do have adequate tidal velocity within the study area do not meet suitable depth requirements, especially increased depth needs for sites located in shipping channels. More detailed suitability modeling within Grays Harbor and Willapa Bay may reveal suitable sites at smaller scales than the current analysis. In addition, we used only the average velocities as a threshold. Calculation of the amount of time velocities exceeds this threshold would more accurately determine site suitability but was not addressed in this project.

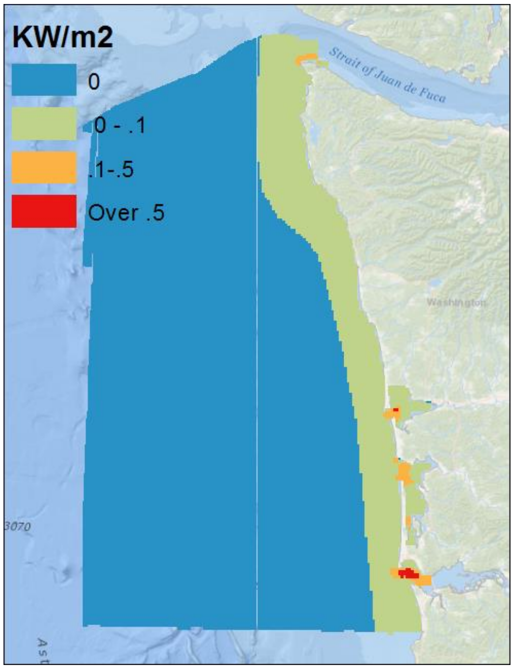

Figure 16. Tidal Energy Potential
Few areas with suitable tidal potential, though lowering the threshold would increase

This study examines large areas of renewable energy feasibility appropriate for a coast-wide spatial planning effort. The 1.44 square kilometer (0.56 mi^2) size of *sites* in this analysis limits the scale of appropriate interpretation. For example, there is one depth value for each non estuarine site which spans 1.44 square kilometer. Across the study area, this resolution provides a good representation of depth. However, within a site, there could be topographic variations with underwater ridges and valleys that are not captured at this resolution. Our objective is to identify suitability of relatively large zones rather than to evaluate individual project sites, although some of this work has been done by others. For limited site specific evaluation, see Hagerman et al. (2004).

Given this objective and the known uncertainty both in the models and data, the suitability results for large, contiguous areas should be viewed with more confidence than for individual, small areas. Furthermore, sites located in the core of a classification are more likely to be correctly assessed than those areas towards the edge of a classification.

4.1 Model Uncertainty

Detailed cost estimates for project planning, resource characterization, site assessment, permitting, construction, maintenance, and decommissioning would provide more accurate cost projects for improved spatial analysis. For example, rather than using a “distance to shore” calculation for the potential cost of underwater transmission cables, the actual cost per mile could be used. This would enable a better understanding of tradeoffs between resource potential and cost.

In addition, there are known inaccuracies within some datasets used. Due to the practical challenges of shallow water data collection, the wave resource data, for example, has known inaccuracies in nearshore waters (EPRI 2011). While we modified our scoring to account for this uncertainty, better data could improve model projections. Likewise, the offshore substrate data are sparse. The nearest field sample value was assigned to most sites. Sampling substrate in each of 24,291 sites is labor and resource intensive and unlikely to occur. In future assessments, substrate type may be an attribute best considered when siting a project rather than in models at ~1 km scales given the lack of data and the heterogeneity of bottom type.

Since NREL completed their offshore wind energy resource assessment at 90 meters (295 feet) above the surface, wind tower heights have continued to increase to as tall as 150 m (~500 feet) (Banister 2013). Updated wind speed estimates may provide for more accuracy. Also, information was not readily available for laydown yard space for onsite assembly or maintenance. Compilation of data for this attribute would improve the accuracy of the nearshore wave energy models.

Finally, more industry advisor participation could add important information about attributes, attribute scores, or model weighting.

4.2 Implications for Washington Marine Spatial Planning

One of many questions considered in Washington’s CMSP process is “what are the appropriate boundaries to Washington’s Marine Spatial Plan?” This study suggests a practical limit for marine renewable energy suitability. Even though wind and wave energy resources exist further offshore, the need for shore-side support and grid connectivity effectively limited the most suitable areas within 25 miles from shore.

The differences in suitability maps among technologies (e.g., wind devices versus wave devices), suggest that planning for marine renewable energy technologies should consider the technologies separately, planning for each technology’s distinct needs, constraints, and impacts rather than planning for marine renewables in aggregate. In terms of evaluating impacts and obtaining permissions, this suggestion is supported by the differences in regulatory regimes for offshore wind energy versus marine hydrokinetic energy (wave and tidal).

Expansions or updates in port or grid infrastructure, improvements to marine renewable devices, and changing market forces all could have large impacts on suitability. Major public sector investments or incentives could also have a substantial impact on suitability or could result in project development in a location that is not highly suitable according to this analysis, but is, for a reason outside the current scope, otherwise desirable.

In a regional energy market, renewable energy development opportunities in neighboring states could have significant impacts on development trends. Whether renewable energy development is a preferred new use of Washington coastal waters or not, it will likely be informative to consider development policies and plans in Oregon and California.

5 Conclusions

This study attempts to shed light on one of many potential uses of ocean space and resources currently under consideration in Washington State's CMSP process. The results of this study are in no way intended to be interpreted as a recommendation to develop marine renewable energy in certain locations. The study shows that for a range of existing technologies and devices and considering basic technical and economic factors, there are many areas potentially suitable for marine renewable energy development off the Washington coast. The results are intended to be used by state agencies and coastal stakeholders in spatial planning considerations for marine renewable energy. These results may also be of interest to federal agencies and regional organizations involved in CMSP and to prospective renewable energy project developers.

This study considers attributes of site quality (energy resource, water depth, substrate), grid connection (distance to shore, kV line, and substation), and shore-side support (distance to service and deepwater ports); applies weighting in a multi-criteria decision analysis to reflect relative importance of attributes; and presents analysis results in terms of basic technical and economic suitability in a series of maps. It is important to note that the structure of the analysis is such that potential sites for non-grid connected projects would be overlooked and that small-scale projects were not considered. Indeed, according to the best available geospatial data for offshore wind and wave energy, most sites have favorable wind and wave energy resources.

Analyses of this type are intended for early planning stages because it suggests spatial areas to focus on during planning for various ocean activities. The resolution of this analysis is appropriate to inform relative suitability for coast-wide marine renewable energy feasibility evaluation but too coarse to accurately inform site specific project planning. CMSP is often simplistically described as a process where layers of spatial data are compiled and then overlaid to produce a spatially explicit map of all existing and future ocean activities.[6] The purpose of this overlay exercise is to illuminate areas where incompatible uses overlap and cause conflicts or areas of opportunity for new or traditional uses. Armed with information about what activities are occurring where, decision makers must consider conflicts and opportunities temporally, and then prioritize and allocate ocean uses over both time and space. This process is heavily data-reliant and complex but also depends heavily on social values and economic priorities, for which no data sets exists. This study appropriately is limited to providing decision makers (e.g., Washington state agencies, the WCMAC, and the public) with basic information about where marine renewable energy could be most likely off the Washington coast.

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[6] Examples of ocean uses include fishing, shipping, and marine transportation; dredging activities; environmental protection; recreation and aesthetic enjoyment; scientific research; and other industrial uses such as marine renewable energy or mineral extraction.

Marine renewable energy as a potential new use of ocean space and resources is viewed favorable by some as a local, renewable energy source offering new opportunities for employment, economic development in coastal communities, increased energy independence, and a role for the state in a new and innovative industry. Others are concerned that marine renewable energy could displace traditional ocean activities or negatively impact the marine environment, coastal recreation, ocean views, or the electricity grid. Ultimately these potential benefits and impacts will need to be evaluated in response to an actual proposed project; building a framework for consideration of societal values and local, state, and national priorities around ocean uses in a spatial context is essential for good decision making and fundamental to the concept of marine spatial planning as articulated at the highest level of government (e.g., Executive Order 13547).

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Appendix A: Additional Detail on Technologies

Technology		**Device Type**	**Industry Advisor**
Offshore Wind	(1) Floating Platform	WindFloat	Principle Power
	Fixed Foundation *(two models)*	(2) Monopile	Offshore Development Coalition
		(3) Jacket/Tripod	
Wave	Nearshore Wave *(two models)*	(4) Oyster	Aquamarine
		(4) SurgeWEC[a]	Resolute Marine Energy
		(5) M3 Delos-Reyes Marrow	M3 Wave Energy Systems, LLC
	(6) Mid-Depth Wave	Rotating Mass Turbine WEC	Neptune Wave Power , LLC
	(7) Deepwater Wave	StingRAY	Columbia Power Technologies, LLC
		PowerBuoy	Ocean Power Technologies, Inc.
	All wave	All	Northwest Energy Innovations/ Pacific Energy Ventures
			NNMREC[b]/Oregon State University
Tidal	(8) Tidal	Turbine Generator Unit (TGU)	Ocean Renewable Power Company, LLC
		All	NNMREC[b]/University of Washington

Numbers indicates the eight device types modeled.

[a] *Wave Energy Converter*

[b] *Northwest National Marine Renewable Energy Center*

Although we are not able to provide detailed specifications on device types within the current scope of work, the text compiled below provides basic information for those unfamiliar with marine renewable technologies. However, the technologies and devices are evolving rapidly. Current information is available at the U.S. Department of Energy's Marine and Hydrokinetic Technology Database.[1]

Offshore Wind

Offshore wind farms have been operating successfully in European waters since 1991. While there are now more than 1,662 offshore wind turbines generating power for European electric users, the first wind turbine in U.S. waters has yet to be installed. This will change in the relatively near future, as planning for offshore wind farms is in advanced stages in the United States, including locations along the Atlantic seaboard, Great Lakes, and Gulf Coast of Texas.[2]

The American offshore wind industry has already benefited a great deal from the experiences and lessons of European developers and equipment manufacturers. As a result, it is expected that the number of offshore wind farms operating in U.S. waters will grow significantly once the necessary local infrastructure (ports, vessels, and supply chain manufacturing) is established. Furthermore, environmental studies conducted at European offshore wind farm sites, both pre- and post-construction, will serve to help inform U.S. regulators

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[1] Marine and Hydrokinetic Technology Database:
http://www1.eere.energy.gov/water/hydrokinetic/GlobalProjectMap.aspx

[2] Source: Offshore Wind Development Coalition

and wind farm developers about the types of research and studies that must be performed to ensure protection of the environment so that the required permits can be issued.

Floating Platform

WindFloat

Principle Power – www.principlepowerinc.com

WindFloat is a floating support structure for offshore wind turbines with a simple, economic, and patented design. The innovative features of the WindFloat dampen wave and turbine induced motion, enabling wind turbines to be sited in previously inaccessible locations where water depth exceeds 50 meters and wind resources are superior. Further, economic efficiency is maximized by reducing the need for offshore heavylift operations during final assembly deployment and commissioning. Multiple projects are in development for the installation of commercial WindFloat units in both European and U.S. offshore wind farms.

There are three advantages to the WindFloat foundation: first, its static and dynamic stability provides sufficiently low pitch performance enabling use of commercial offshore wind turbines; second, its design and size allow for onshore assembly; and third, its shallow draft allows for depth independent siting and wet tow (fully assembled and commissioned) to sites not visible from shore. Primary markets are transitional (30 to 60 meters) and deep (greater than 60 meters) water offshore wind sites in the U.S. and Europe, previously inaccessible, and estimated to have greater than 2 terawatt (TW) of resource potential. Secondary markets include sites in Asia and other Oceanic countries.

Fixed Foundation

Offshore Development Coalition – www.offshorewinddc.org/

Information for the monopile, jacket, and tripod foundation was acquired from http://www.lorc.dk.

Monopile

The most popular foundation for an offshore wind turbine is a monopile. The large steel pipe is by far the most popular turbine support structure in the world. At the end of 2012, 1,923 of the world's 2,688 offshore wind turbines used monopiles for support.

The reasons are several:

- Simplicity in design and production – it is a long tube, making both calculations and production manageable;
- The shape allows for effective transportation to site; and,
- The installation technique is well known and widely used by the construction industry.

The monopile typically weighs around 500 tons, making it one of the lighter support structures. On deeper sites like Walney 2, the monopiles weigh up to 810 tons and are up to 69 meters long.

Considering all factors, monopiles are a well-suited choice for support structure in water depths ranging from 0 to 25 meters.

Jacket

When power companies began to look at deeper waters for installing wind turbines they had to consider alternative support structures. Thus, the jacket structure entered the sector and moved the boundaries. Until 2007, other structures such as the monopile and gravity-based structures had only been able to put wind turbines at a water depth of 20 meters.

But the Beatrice demonstrator project in the UK changed that. Making a leap from 20 to 45 meters water depth, it strongly suggested that the jacket structure had something to offer in terms of large depths.

The concept of jackets is inherited from the oil and gas industry. Jackets have been used for supporting rigs at a depth of more than 100 meters.

A jacket is made up of three or four main legs, connected to each other by bracings. All elements are tubular unlike onshore lattice structures which are usually made from angular profiles.

Tripod

The structure is common in the offshore oil and gas industry. So far, only the German wind farm Alpha Ventus uses tripods to support six of their wind turbines, the Areva Multibrid 5000. There is nothing small about the dimensions, though. The tripod is made out of 700 tons of steel, and three piles 40 meters in length are needed to secure it. The structure consists of a central column, diagonal bracings, and three supporting sleeves with mud mats. Through each sleeve is placed a pile, which is driven into the seabed and connected to the sleeve with concrete or grouting.

Instead of using sleeves with mud mats and piles, the tripod can also be founded with suction buckets. But this has not been used in wind farms yet. The three feet give the tripod good stiffness and stability against overturning. This makes it more suitable for larger water depths than the monopile. The depth ranges from 20 to 50 meters.

But compared to jackets, the tripod is more prone to wave loads because the large diameter of the steel tubes results in a large surface area. And the main joint at the central column poses an engineering challenge – it is receptive to fatigue and complex to design.

Wave

Wave energy technology is still young in its development and many trial wave energy conversion devices have been developed but no single technology has been proven superior. Development and testing of a variety of devices is being carried out in all corners of the world.

Wave energy converters capture energy from the heave (up and down), surge (back and forth), the pitch (rolling) motion of a wave, or through a multi-mode device that interacts with the all elements of the wave. Point absorber devices, for example, interact with the heave (vertical) component of the wave, while flap devices interact with the surge (horizontal) component. The devices below capture energy in various different waves and range in location from being placed near the shoreline to deep water.

Nearshore Wave

Oyster

Aquamarine Power: www.aquamarinepower.com

Wave power is generated by wind blowing over the surface of the ocean far out at sea. The action of the wind transmits energy into waves. These waves can travel vast distances with little energy loss before breaking on the shore. Aquamarine Power's Oyster wave power technology captures energy in nearshore waves and converts it into clean sustainable electricity. Essentially, Oyster is a wave-powered pump which pushes high pressure water to drive an onshore hydro-electric turbine. The device is designed to harness this energy and convert it into electricity.

The Oyster wave power device is a buoyant, hinged flap which is attached to the seabed at depths of between 10 and 15 meters, around half a kilometer from the shore. Oyster's hinged flap, which is almost entirely underwater, pitches backwards and forwards in the nearshore waves. The movement of the flap drives two hydraulic pistons which push high pressure water onshore via a subsea pipeline to drive a conventional hydro-electric turbine.

The advantage of locating the Oyster in the nearshore is to continue to have the ability to capture a high proportion of the energy available in the ocean while avoiding the severe storms which occur further out to sea.

In the future, subsea pipelines will connect multiple Oyster wave energy devices to a single onshore plant. Ultimately Oyster will be installed in wave farms of several hundred connected devices generating hundreds of megawatts of electricity.

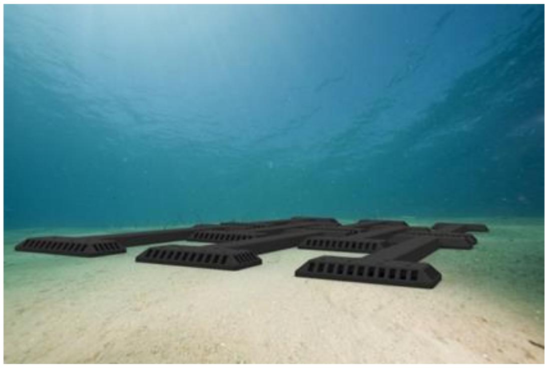
SurgeWEC^{TM}

Resolute Marine Energy (RME), Inc. – www.resolutemarine.com

Resolute Marine Energy (RME) is developing an Oscillating Wave Surge Converter (trade named SurgeWEC^{TM}) which is a seabed-mounted hinged flap that oscillates in response to waves passing overhead and pressurizes a fluid which is piped ashore to generate electricity or directly-drive a reverse osmosis desalination system. RME chose to develop and commercialize SurgeWEC^{TM} because it is deployed near shore in relatively shallow water (short energy transmission distances = lower costs) and, being bottom-mounted, it is relatively easy to protect from storm damage. In December/January of 2012/2013 a full-scale SurgeWEC^{TM} prototype was deployed and tested in the ocean at the U.S. Army Corps of Engineers field research facility in Duck, NC. RME is currently developing a small wave energy project for a rural community in Alaska that is dependent upon diesel generators for its electricity supply.

M3 Delos-Reyes Marrow

M3 Wave Energy Systems, LLC – www.m3wave.com



The Delos-Reyes Morrow Pressure Device, or DMP, is an innovative new approach to the concept of extracting energy from the ocean. Originally developed in 1991, the DMP is being commercialized by M3 Wave Energy Systems, LLC, in the Pacific Northwest region of the United States.

The DMP operates beneath the surface of the ocean, avoiding many of the issues inherent with surface-based systems like ocean power buoys, ocean wind farms, and floating photo voltaic. Submerged operation reduces the impact on commercial navigation, recreation, fisheries, marine animals, aesthetics, and sea birds. Residing under the surface also protects the DMP from some of the harsh aspects of the ocean environment: wind loading, inclement weather, rogue waves, UV damage, etc. Additional benefits include tow-to-site self-deploying and recovery capability, enhanced power source security, and stealthy power generation potential for military applications.

Mid-Depth Wave

Rotating Mass Turbine WEC

Neptune Wave Power, LLC – www.neptunewavepower.com

Neptune Wave Power’s technology is a “point absorber” Wave Energy Conversion Device (WECD). The floating and securely moored offshore buoy reacts to the vertical surge and irregular movement of waves causing a horizontal pendulum within it to rotate. The rotational energy of this pendulum, through a proprietary internal drive system, is directed to an on board electric generator. Power generated is fed to the utility grid via an underwater cable system at an interconnect point. Neptune Wave Power’s WECD patented designs have numerous advantages:

- No moving parts exposed to seawater.
- Design that uses proven electrical, mechanical, mooring, and drive components.
- Modular design for cost effective manufacturing.
- Interchangeable components for cost effective maintenance.
- Scalable and movable.
- Dynamically configurable for any offshore environment.
- Operational in sea wave heights as small as 1 foot.

Deepwater Wave

StingRAY

Columbia Power Technologies, Inc. – www.columbiapwr.com

The StingRAY system is based on a design philosophy that values simplicity, high efficiency, and durability. Columbia Power's StingRAY wave power system is meant to be deployed in water depths over 60 meters and arrayed in "farms" much like wind turbines. The wave farms are usually located at least 1 to 2 miles from shore; away from the coastline and the sensitive habitats contained there.

At a high level, the StingRAY captures energy from each passing wave and produces electricity on-board the device. The electricity generation process includes a series of steps starting with the transfer of captured energy from the forward and aft floats to two rotary, low-speed, high-torque electric generators on board the StingRAY. The generated power is then conditioned to stable, electric-grid-compatible output. In a wave farm, this electricity is centrally collected in an offshore "sub-station" for transmission ashore and connection to the grid.

PowerBuoy

Ocean Power Technologies, Inc. – www.oceanpowertechnologies.com

Since 1994, OPT has focused on its proprietary PowerBuoy technology, capturing wave energy using large floating buoys anchored to the sea bed and converting that energy into electricity using innovative power take-off systems.

The PowerBuoy's wave generation system uses a "smart," oceangoing buoy to capture and convert wave energy into low-cost, clean electricity. The rising and falling of the waves offshore causes the buoy to move freely up and down. The resultant mechanical stroking is converted via a sophisticated power take-off to drive an electrical generator. The generated wave power is transmitted ashore via an underwater power cable. An Ocean Power Technologies power station would have a very low "surface profile. It is barely visible from shore.

Sensors on the PowerBuoy continuously monitor the performance of the various subsystems and surrounding ocean environment. Data is transmitted to shore in real time. In the event of very large oncoming waves, the system automatically locks up and ceases power production. When the wave heights return to normal, the system unlocks and recommences energy conversion and transmission of the electrical power ashore.

WET-NZ

Northwest Energy Innovations/Pacific Energy Ventures – www.nwenergyinnovations.com

The Wave Energy Technology New Zealand (WET-NZ) is a "multi-mode" device that interacts with the heave, surge, and pitch components of the wave to maximize the amount of energy captured.

The WET-NZ makes maximal use of the device's wetted surfaces to transfer wave forces to the structure, operating in heave motion similarly to other point absorber technologies, as well as capturing surge and pitch energy through the horizontal motion of the reactive hull and the active float. Once the device is deployed, ballast tanks in the hull are flooded with seawater to increase its mass so that it does not move vertically to track the wave profile; as a result, the device can still capture surge and pitch motions of the wave.

The Active Float pivots about a single axle between the hull and the power pod at the waterline. Excited by both vertical and horizontal motions of the waves, the active float rotates about the pivot to create relative motion between the two parts. By opposing this differential movement, additional energy is extracted.

A key feature of the WET-NZ design is that the active float can rotate continuously through 360 degrees or oscillate back and forth at will, enabling the device to extract energy from both situations. In addition, the float's ability to fully rotate prevents the hydraulic rams and structure from being over-stressed at the extremes of motion – an issue that has caused other wave energy technologies to suffer hydraulic ram failures during testing, because – by design – they have to restrict the float motion with end-stops.

The fully rotating float also provides a self-limiting power shedding effect, which makes the device inherently survivable in open ocean environments and helps to reduce mooring loads.

Tidal

Turbine Generator Unit

Ocean Renewable Power Company, LLC – www.orpc.co/

The Ocean Renewable Power Company (ORPC) power systems are designed around their proprietary Turbine Generator Unit (TGU). The TGU works on the same principle as a wind turbine, with rotating foils that power a central permanent magnet generator. The TGU is installed underwater and because water is more than 800 times denser than air, the TGUs provide significantly more power than wind turbines at relatively low water current speeds. Built primarily with composite materials, they resist corrosion in fresh and salt water alike. As gearless units, they require no lubricants, and emit absolutely nothing into the surrounding water.

At river and ocean energy sites, ORPC installs TGUs in groups to form complete power systems that convert river and ocean energy into grid-compatible power. The TGU has a modular design that makes it easy to adapt to the varying needs of different site environments. To install power systems at small river and shallow tidal sites, the TGUs are secured to the riverbed or seabed using bottom support frames. To use the technology at deeper tidal and deep ocean current sites, the TGUs are stacked together to form larger, more powerful modules, which are moored to the sea floor with a deep sea mooring system. Because the modules are buoyant, they can be suspended above the sea floor at a depth that's safe for both sea vessels above and sea life below.

ORPC's power systems produce no emissions and require no fossil fuels to operate, deriving their power solely from the renewable resource of the earth's rivers and oceans. Since these currents are both regular and completely predictable, the clean, dependable energy generated by ORPC power systems can be scheduled years in advance.

ORPC's TidGen® Power System, designed to generate electricity at water depths of 50 to 100 feet, is used at shallow tidal and deep river sites. A permanent-magnet generator mounted between the four turbines produces up to 150 kilowatts. The TidGen's helical turbines have teardrop-shaped foils and rotate in a single direction, regardless of the flow of the current. In this system, groups of TGUs connect directly to an on-shore substation through a single underwater transmission line. The TidGen® Power System is larger and more powerful than the RivGen™ Power System, with each TGU having a rated capacity of 150 kilowatts.

Appendix B: Full Description of Attributes and Data Sources

Site Suitability					
	Attribute Measured	**Datasets**	**Source**	**Description**	**Processing**
1	Depth	Topography	Scripps Institute of Oceanography. http://topex.ucsd.edu/WWW_html/srtm30_plus.html; NOAA estuarine bathymetry	Point Bathymetry Grid from Soundings.	Converted to 1000 m raster dataset. Reclassified into ten depth categories (Scripps).
2	Substrate	usSEABED	USGS Coastal and Marine Geology. http://pubs.usgs.gov/ds/2006/182/usseabed.html	Point dataset from multiple sediment sampling efforts. Includes Phi value and likelihood of rocky bottom for most sample location.	Created polygon dataset based on point dataset to cover study area. As attributes different, used Phi scale to convert to Wentworth classification (Cobble, gravel, sand or mud). Used Rocky bottom attribute to identify areas of Rock. *One of the datasets of least confidence
3	Tidal Energy	Mean Tidal Density	Georgia Institute of Technology. http://www.tidalstreampower.gatech.edu/	Point dataset	Converted to 250 m raster dataset
4	Wind Energy	Pacific Northwest Regional Wind 50 m Wind Power Estimates. Pacific Coast; 90 m Windspeed Offshore	NREL. http://www.nrel.gov/gis/data_wind.html	Polygon Datasets	Convert to raster at 250 m
5	Wave Energy	Wave Power Density	NREL. http://www.nrel.gov/gis/data_mhk.html	Polygon Dataset	Convert to raster at 250 m

Grid Feasibility

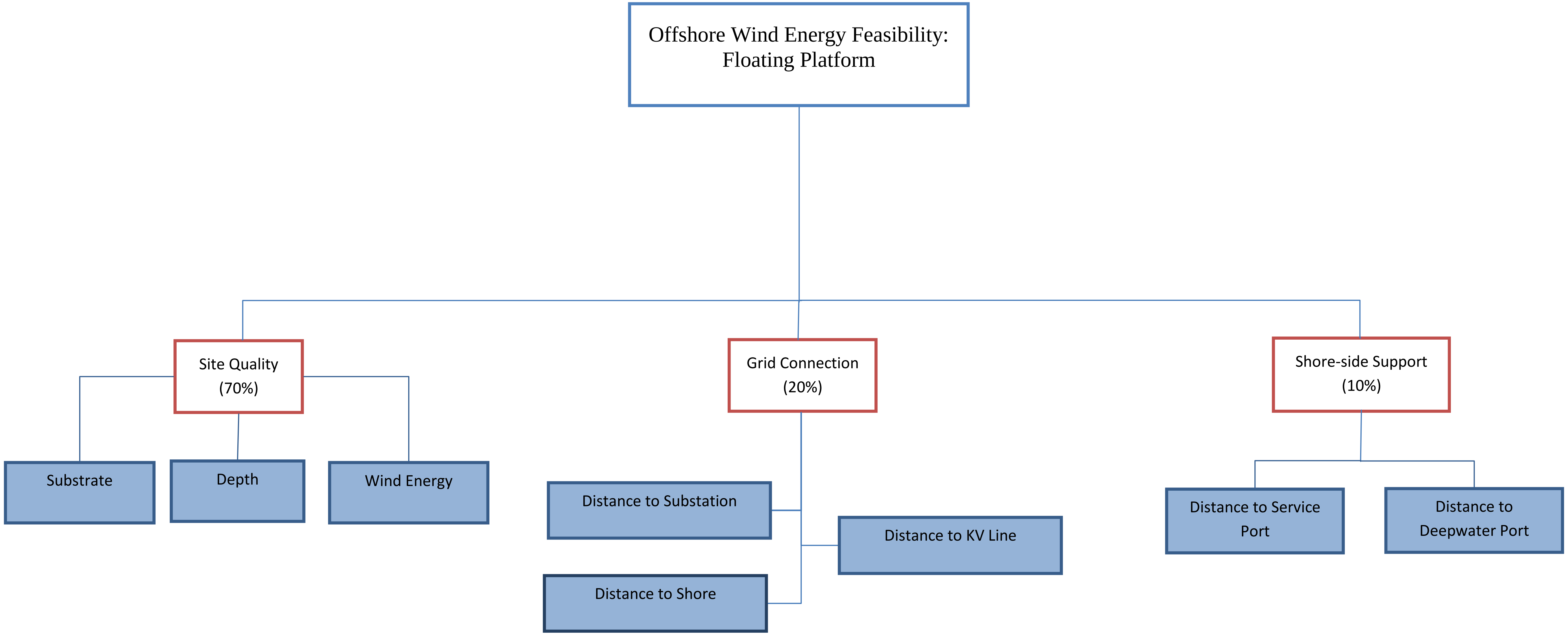
	Attribute Measured	Datasets	Source	Description	Processing
1	Distance to Substation	Substations	BPA. Clallam County, Grays Harbor, and Pacific Counties	Created new point dataset, appending all Substation Points into one dataset.	Calculated Distance in Nautical Miles to nearest substation, Using a 250 m Cell Size and Euclidean distance
2	Distance to Shore	State of Washington	Washington Dept of Ecology	Polygon Dataset; Select those polygons identified as land	Calculated Distance in Nautical Miles to shore, Using a 250 m Cell Size and Euclidean distance
3	Distance to Transmission Line	Transmission Lines	BPA. USGS. Clallam County, Grays Harbor, and Pacific Counties	Created polyline dataset, appending all Transmission Line Records into one dataset.	Calculated Distance in Nautical Miles to nearest line, Using a 250 m Cell Size and Euclidean distance

Shore-Side Support

	Attribute Measured	Datasets	Source	Description	Processing
1	Distance to Service Port	All Ports	USACE Navigation Data Center: http://www.ndc.iwr.usace.army.mil/db/gisviewer	Points Dataset; Subselection of Washington Coast	Calculated Distance in Nautical Miles to Nearest Port, using a 250 m Cell Size and Euclidean distance
2	Distance to Deepwater Port	Principal Ports	USACE Navigation Data Center: http://www.ndc.iwr.usace.army.mil/db/gisviewer	Points Dataset; Reviewed. Selected Closest to Study Area and Added Astoria. Includes 3 ports: Grays Harbor, Port Angeles and Astoria	Calculated Distance in Nautical Miles to Nearest Principal Port, using a 250 m Cell Size
3	Distance to Airports	Created Airports of Interest	Washington Department of Transportation	All airports on the coast that also had access to Helicopter Fuel	Distance in nm to digitized relevant airports http://www.wsdot.wa.gov/geosvcs/

Units of Assessment. OCS blocks, subdivided into 1.2 km cells. *Source*: BOEM.

Appendix C: Conceptual Models and Attribute Tables



Model: **Offshore Wind Energy Feasibility: Floating Platform**

Key:

Sub-model (Weighting)

Attribute

Model Link

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest NATIONAL LABORATORY Parametrix

Model Specifications – Floating Platform

Background

This model evaluates the feasibility of siting full scale offshore wind energy devices in a pre-commercial context (projects of 1-5 turbines). Considering turbine output of 5-6 MW, offshore wind projects may generate significant power (5-30 MW). As a result, the proximity of shore side support and grid connection are relatively less important than wind resource. This relative importance is reflected in weighting applied to each submodel.

Floating foundations considered include ballast-stabilized spar buoys and buoyancy-stabilized, semi-submersible platforms. Structures are tethered to the seafloor with catenary mooring lines and drag embedment anchors.

Suitability Evaluation

The three sub-models that inform offshore wind energy feasibility for turbines mounted on floating platforms include site quality, grid connection, and shore-side support.

The Site Quality Sub-model considers the wind resource at 90 meters above the sea surface, water depth, and the suitability of the seafloor substrate for anchoring floating platforms.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line.

The Shore-side Support Sub-model for floating platform offshore wind considers assembly, installation, and maintenance activities. In this case only distance to a deepwater port for installation is considered because helicopters would likely be used for routine maintenance, making distance to a service port irrelevant. Because turbines are installed upright onto platforms in port and towed out to the project site, suitable deepwater ports have unobstructed overwater access to sea with a clearance of >180 m (Banister 2013).

Site Quality Sub-Model

Attribute: Mean Annual Wind Speed*

Ref.	Classification	Score
1	0-6.0 m/s	0
2	6.0-6.5 m/s	2
3	6.5-7.0 m/s	5
4	7.0-7.5 m/s	9
5	> 7.5 m/s	10

*Measured at 90 meters above the surface

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	0
2	10m < 20m (5.5-10.9)	0
3	20m < 30m (10.9-16.4)	0
4	30m < 40m (16.4-21.9)	0
5	40m < 50m (21.9-27.3)	5
6	50m < 60m (27.3-32.8)	8
7	60m < 200m (32.8-109.4)	10
8	200m < 300m (109.4-164)	9
9	300m < 1000m (164-546.8)	8
10	>1000m (>546.8)	7

Attribute: Substrate

Ref.	Classification	Score
1	Rock	1
2	Gravel	2
3	Sand	3
4	Cobble	2
5	Mud	3

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	7
4	15 NM < 20 NM	4
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	1 NM < 5 NM	10
2	5 NM < 10 NM	8
3	10 NM < 15 NM	6
4	15 NM <20 NM	3
5	> 20 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	9
3	6 NM < 9 NM	8
4	9 NM < 12 NM	4
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

Attribute: Distance to Service Port

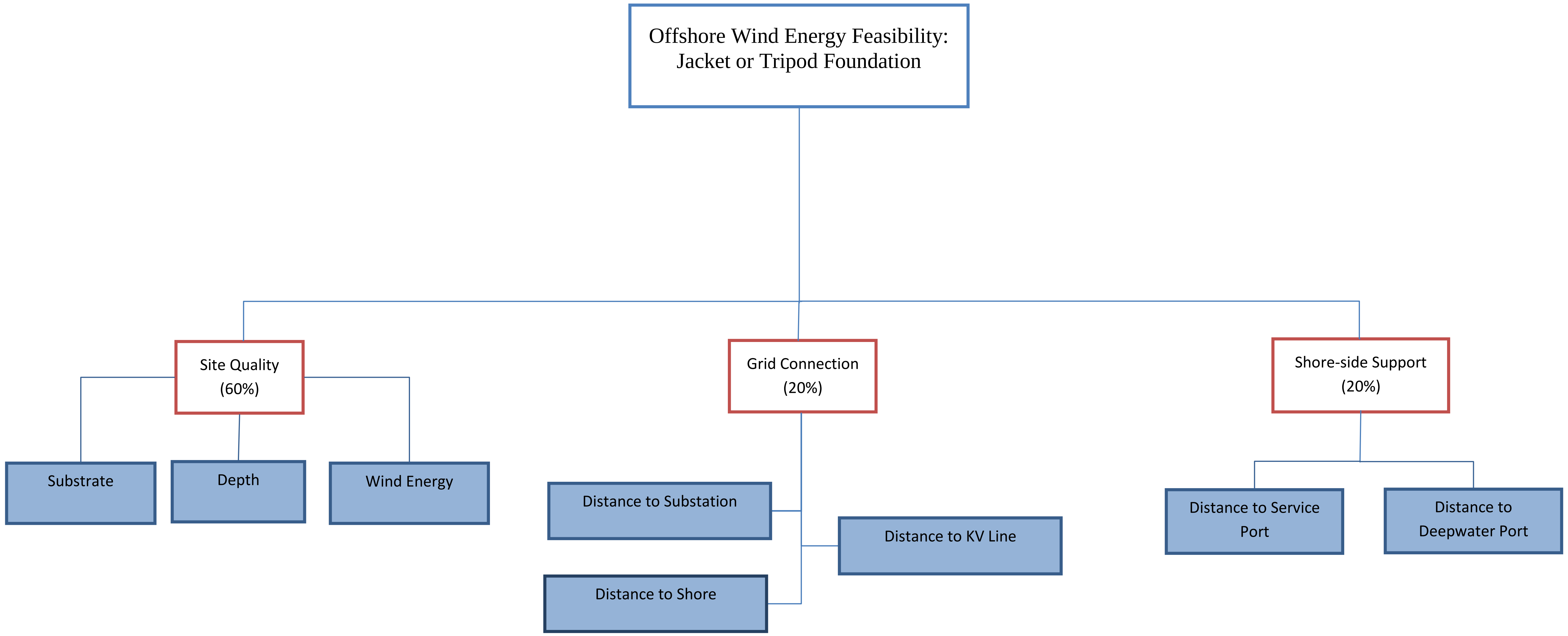
Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port*

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	10
3	10 NM < 20 NM	10
4	20 NM < 30 NM	9
5	30 NM < 40 NM	8
6	40 NM < 50 NM	7
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

*If ocean access from the port is blocked by an overwater structure > 180m, the port is not considered.

Resources: Banister 2013, Copping 2013, EWEA 2009, Main(e) International Consulting 2012, Musial and Ram 2010, OWET 2010, States et al. 2012, WPA 2013



Model: **Offshore Wind Energy Feasibility: Jacket or Tripod Foundation**

Key:

Attribute

Sub-Model (Weighting)

Model Link

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest NATIONAL LABORATORY Parametrix

Model Specifications – Jacket or Tripod Foundation

Background

This model evaluates the feasibility of siting full scale offshore wind energy devices in a pre-commercial context (projects of 1-5 turbines). Considering turbine output of 5-6 MW, offshore wind projects may generate significant power (5-30 MW). As a result, the proximity of shore side support and grid connection are relatively less important than wind resource. This relative importance is reflected in weighting applied to each submodel.

Jacket or tripod foundations, considered suitable for "transitional" water depths of 30-60m, include four or three legged steel structures each supporting one turbine. Structures are installed using jack-up barges and are anchored to the seafloor with pies or suction anchors.

Suitability Evaluation

The three sub-models that inform fixed foundation, transitional depth offshore wind energy feasibility include site quality, grid connection, and shore-side support.

The Site Quality Sub-model considers the wind resource at 90 meters above the sea surface, water depth, and the suitability of the seafloor substrate for anchoring floating platforms.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line.

The Shore-side Support Sub-model for transitional depth (i.e., deeper than monopile and shallower than floating platforms) offshore wind considers assembly, installation, and maintenance activities.

Site Quality Sub-Model

Attribute: Mean Annual Wind Speed*

Ref.	Classification	Score
1	0-6.0 m/s	0
2	6.0-6.5 m/s	2
3	6.5-7.0 m/s	5
4	7.0-7.5 m/s	9
5	> 7.5 m/s	10

*Measured at 90 meters above the surface

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	1
2	10m < 20m (5.5-10.9)	5
3	20m < 30m (10.9-16.4)	7
4	30m < 40m (16.4-21.9)	10
5	40m < 50m (21.9-27.3)	9
6	50m < 60m (27.3-32.8)	8
7	60m < 85m (32.8-46.5)	1
8	85m < 100m (46.5-54.7)	0
9	100m < 200m (54.7-109.4)	0
10	>200m (>109.4)	0

Attribute: Substrate

Ref.	Classification	Score
1	Rock	1
2	Gravel	7
3	Sand	8
4	Cobble	4
5	Mud	8

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	7
4	15 NM < 20 NM	4
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	1 NM < 5 NM	10
2	5 NM < 10 NM	8
3	10 NM < 15 NM	6
4	15 NM <20 NM	3
5	> 20 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	9
3	6 NM < 9 NM	8
4	9 NM < 12 NM	4
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

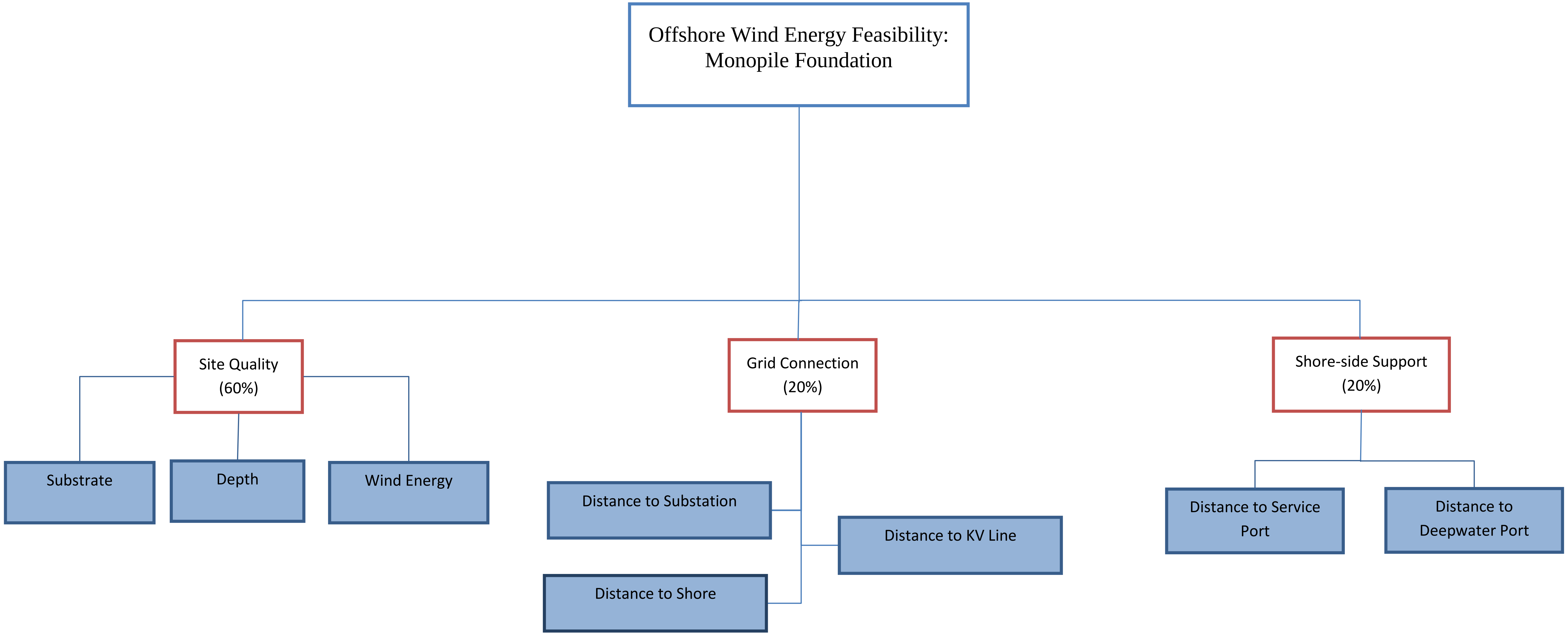
Attribute: Distance to Service Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	10
3	10 NM < 20 NM	10
4	20 NM < 30 NM	9
5	30 NM < 40 NM	8
6	40 NM < 50 NM	7
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

Resources: EWEA 2009, Musial and Ram 2010, OWET 2010, States et al. 2012, WPA 2013



Model: **Offshore Wind Energy Feasibility: Monopile Foundation**

Key:

Attribute

Sub-Model (Weighting)

Model Link

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest NATIONAL LABORATORY Parametrix

Model Specifications – Monopile Foundation

Background

This model evaluates the feasibility of siting full scale offshore wind energy devices in a pre-commercial context (projects of 1-5 turbines). Considering turbine output of 5-6 MW, offshore wind projects may generate significant power (5-30 MW). As a result, the proximity of shore side support and grid connection are relatively less important than wind resource. This relative importance is reflected in weighting applied to each submodel.

Monopile foundations are the most mature offshore wind technology. One turbine is supported by each pile which is driven into the seafloor. Monopile foundations are suitable for water depths up to 30 m.

Suitability Evaluation

The three sub-models that determine offshore wind energy feasibility for monopile foundations include site quality, grid connection, and shore-side support.

The Site Quality Sub-model considers the wind resource at 90 meters above the sea surface, water depth, and the suitability of the seafloor substrate for anchoring floating platforms.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line.

The Shore-side Support Sub-model considers assembly, installation, and maintenance activities.

Site Quality Sub-Model

Attribute: Mean Annual Wind Speed*

Ref.	Classification	Score
1	0-6.0 m/s	0
2	6.0-6.5 m/s	2
3	6.5-7.0 m/s	5
4	7.0-7.5 m/s	9
5	> 7.5 m/s	10

*Measured at 90 meters above the surface

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	8
2	10m < 20m (5.5-10.9)	10
3	20m < 30m (10.9-16.4)	9
4	30m < 40m (16.4-21.9)	2
5	40m < 50m (21.9-27.3)	0
6	50m < 60m (27.3-32.8)	0
7	60m < 85m (32.8-46.5)	0
8	85m < 100m (46.5-54.7)	0
9	100m < 200m (54.7-109.4)	0
10	>200m (>109.4)	0

Attribute: Substrate

Ref.	Classification	Score
1	Rock	1
2	Gravel	8
3	Sand	7
4	Cobble	5
5	Mud	5

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	7
4	15 NM < 20 NM	4
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	1 NM < 5 NM	10
2	5 NM < 10 NM	8
3	10 NM < 15 NM	6
4	15 NM <20 NM	3
5	> 20 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	9
3	6 NM < 9 NM	8
4	9 NM < 12 NM	4
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

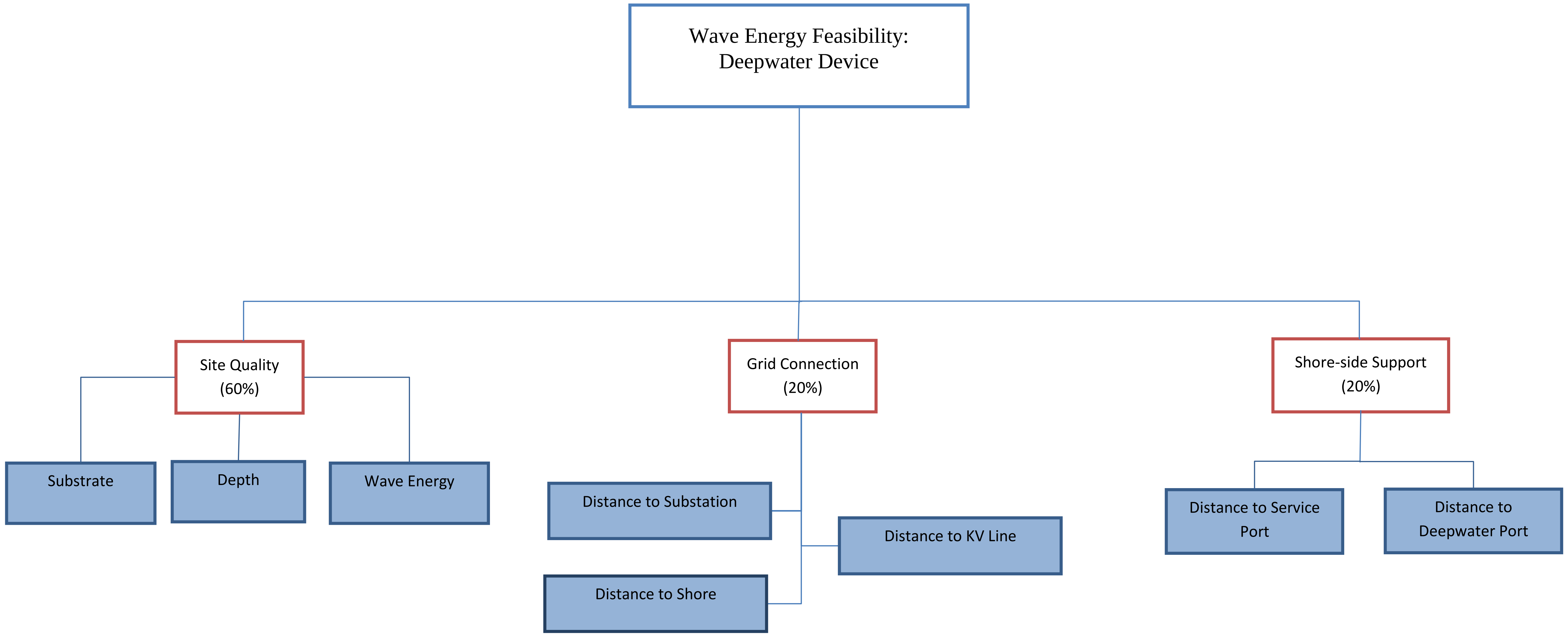
Attribute: Distance to Service Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	10
3	10 NM < 20 NM	10
4	20 NM < 30 NM	9
5	30 NM < 40 NM	8
6	40 NM < 50 NM	7
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

Resources: Banister 2013, EWEA 2009, Musial and Ram 2010, OWET 2010, Pfeister 2013, States et al. 2012, WPA 2013



Model: **Wave Energy Feasibility: Deepwater Device in Economically Constrained Environment**

Key:
Attribute
Sub-Model (Weighting)
→ Model Link

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest NATIONAL LABORATORY Parametrix

Model Specifications – Deepwater Wave Energy Device

Background

The economically-constrained deepwater wave energy device feasibility model evaluates the feasibility of siting offshore wave energy devices, such as point absorber and offshore attenuator/pivot devices, in a full-scale but pre-commercial context. In this context, wave energy devices do not generate sufficient revenue to overcome the importance of proximity to shore-side services and infrastructure. The suitability scoring reflects the financial importance of proximity to shore and a potential grid connection.

Suitability Evaluation

The three sub-models that determine deepwater wave energy feasibility are site quality, grid connection, and shore-side support.

The Site Quality Sub-model considers the wave resource, water depth, and the suitability of the seafloor substrate for anchoring or mounting devices.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line. While connecting to a sub-station is not anticipated to be a necessity for most pre-commercial installations, it is a relevant factor for site expansion opportunity.

The Shore-side Support Sub-model evaluates the ability of existing shore-side resources to satisfy wave energy developers' needs for access to a deepwater port for device installation, and access to a service port for operations and intermittent maintenance.

Site Quality Sub-Model

Attribute: Mean Annual Wave Power Density

Ref.	Classification	Score
1	< 30 kW/m	0
2	≥ 30kW/m	10

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	**0**
2	10m < 20m (5.5-10.9)	**0**
3	20m < 30m (10.9-16.4)	**0**
4	30m < 40m (16.4-21.9)	**2**
5	40m < 50m (21.9-27.3)	**5**
6	50m < 75m (27.3-41)	**9**
7	75m < 85m (41-46.5)	**10**
8	85m < 125m (46.5-68.4)	**10**
9	125m < 150m (68.4-82)	**5**
10	>150m (>82)	**1**

Attribute: Substrate

Ref.	Classification	Score
1	Rock	2
2	Gravel	5
3	Sand	7
4	Cobble	5
5	Mud	7

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	7
4	15 NM < 20 NM	4
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	<1 NM	10
2	1 NM < 2 NM	9
3	2NM < 3 NM	8
4	3 NM < 4 NM	7
5	4 NM < 5 NM	6
6	5 NM < 6 NM	5
7	6 NM < 7 NM	4
8	7 NM < 8 NM	3
9	8 NM < 9 NM	2
10	9 NM < 10 NM	1
11	> 10 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	9
3	6 NM < 9 NM	8
4	9 NM < 12 NM	4
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

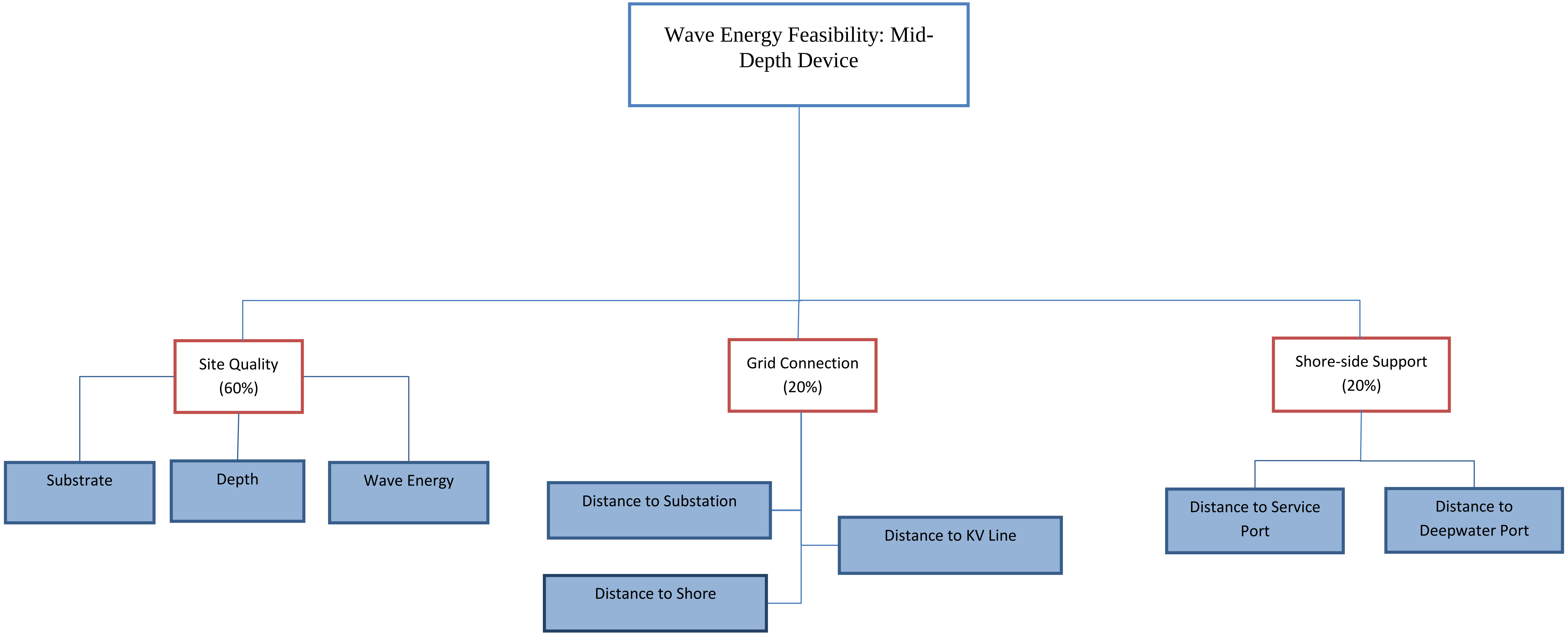
Attribute: Distance to Service Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 20 NM	8
4	20 NM < 30 NM	7
5	30 NM < 40 NM	6
6	40 NM < 50 NM	5
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

Resources: Batten 2013, EPRI 2005, Klure 2013, Lurie 2013, Lesemann 2013, OWET 2010, Ozkan-Haller 2013, Rezza 2013



Model: **Wave Energy Feasibility: Mid-Depth Device in Economically Constrained Environment**

Key:

Attribute

Sub-Model (Weighting)

Model Link

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest NATIONAL LABORATORY Parametrix

Model Specifications – Mid-Depth Wave Energy Device

Background

The economically-constrained mid-depth wave energy device feasibility model evaluates the feasibility of siting offshore wave energy devices, such as oscillating water column, offshore surge, offshore flywheel, and offshore pressure wave energy devices, in a full-scale but pre-commercial context. In this context, wave energy devices do not generate sufficient revenue to overcome the importance of proximity to shore-side services and infrastructure. The suitability scoring reflects the financial importance of proximity to shore and a potential grid connection.

Suitability Evaluation

The three sub-models that determine mid-depth wave energy feasibility are site quality, grid connection, and shore-side support.

The Site Quality Sub-model considers the wave resource, water depth, and the suitability of the seafloor substrate for anchoring or mounting devices.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line. While connecting to a sub-station is not anticipated to be a necessity for most pre-commercial installations, it is a relevant factor for site expansion opportunity.

The Shore-side Support Sub-model evaluates the ability of existing shore-side resources to satisfy wave energy developers' needs for access to a deepwater port for device installation, and access to a service port for operations and intermittent maintenance.

Site Quality Sub-Model

Attribute: Mean Annual Wave Power Density

Ref.	Classification	Score
1	< 30 kW/m	0
2	≥ 30 kW/m	10

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	**1**
2	10m < 20m (5.5-10.9)	**8**
3	20m < 30m (10.9-16.4)	**10**
4	30m < 40m (16.4-21.9)	**8**
5	40m < 50m (21.9-27.3)	**6**
6	50m < 75m (27.3-41)	**4**
7	75m < 85m (41-46.5)	**2**
8	85m < 125m (46.5-68.4)	**1**
9	125m < 150m (68.4-82)	**0**
10	>150m (>82)	**0**

Attribute: Substrate

Ref.	Classification	Score
1	Rock	8
2	Gravel	10
3	Sand	2
4	Cobble	8
5	Mud	1

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	7
4	15 NM < 20 NM	4
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	<1 NM	10
2	1 NM < 2 NM	9
3	2NM < 3 NM	8
4	3 NM < 4 NM	7
5	4 NM < 5 NM	6
6	5 NM < 6 NM	5
7	6 NM < 7 NM	4
8	7 NM < 8 NM	3
9	8 NM < 9 NM	2
10	9 NM < 10 NM	1
11	> 10 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	9
3	6 NM < 9 NM	8
4	9 NM < 12 NM	4
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

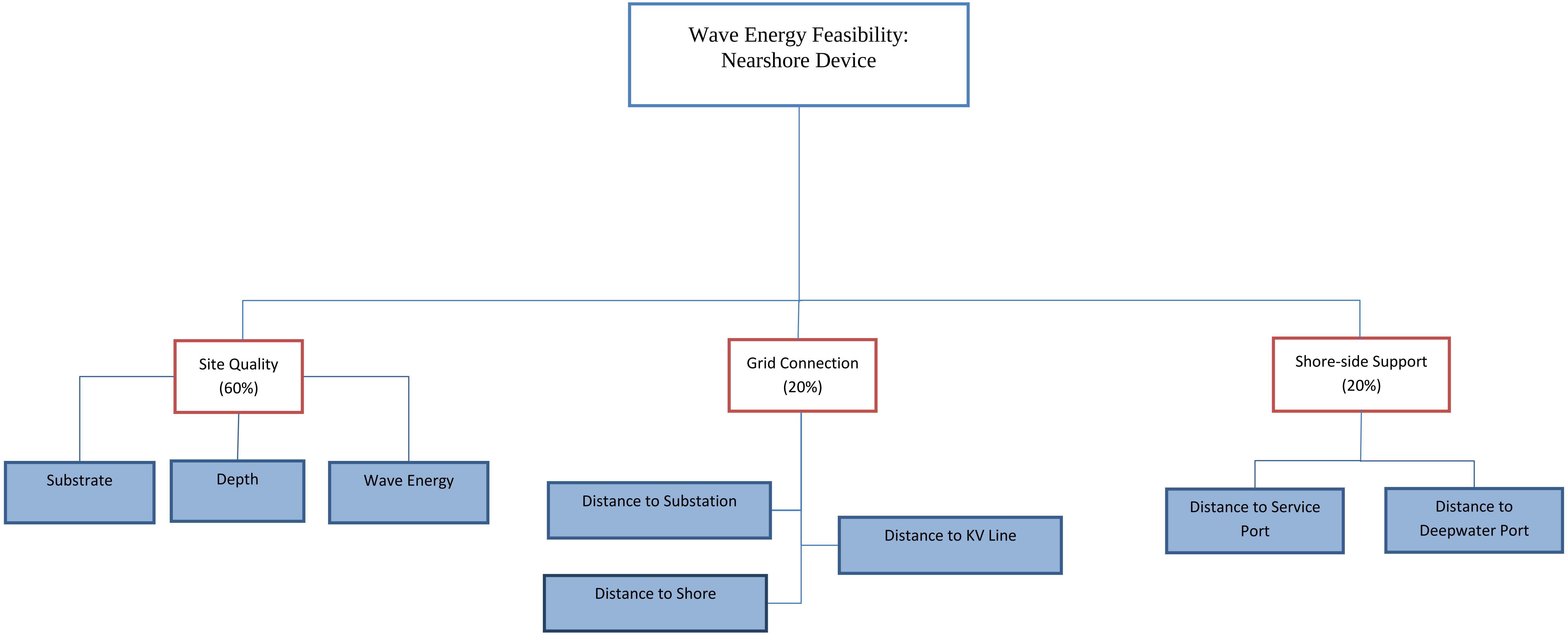
Attribute: Distance to Service Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 20 NM	8
4	20 NM < 30 NM	7
5	30 NM < 40 NM	6
6	40 NM < 50 NM	5
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

Resources: Batten 2013, EPRI 2005, Klure 2013, Morrow 2013, Murray 2013, OWET 2010, Ozkan-Haller 2013, Rezza 2013



Model: **Wave Energy Feasibility: Nearshore Device in Economically Constrained Environment**

Key:
Attribute
Sub-Model (Weighting)
Model Link

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest NATIONAL LABORATORY Parametrix

Model Specifications – Nearshore Wave Energy Device

Background

The economically-constrained nearshore wave energy device feasibility model evaluates the feasibility of siting wave energy devices, such as nearshore converter and coastal surge devices, in a full-scale but pre-commercial context. In this context, wave energy devices do not generate sufficient revenue to overcome the importance of proximity to shore-side services and infrastructure. The suitability scoring reflects the financial importance of proximity to shore and a potential grid connection.

Suitability Evaluation

The three sub-models that determine nearshore wave energy feasibility are site quality, grid connection, and shore-side support.

The Site Quality Sub-model considers the wave resource, water depth, and the suitability of the seafloor substrate for anchoring or mounting devices.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line. While connecting to a sub-station is not anticipated to be a necessity for most pre-commercial installations, it is a relevant factor for site expansion opportunity.

The Shore-side Support Sub-model evaluates the ability of existing shore-side resources to satisfy wave energy developers’ needs for access to a deepwater port for device installation, and access to a service port for operations and intermittent maintenance.

Site Quality Sub-Model

Attribute: Mean Annual Wave Power Density

Ref.	Classification	Score
1	1 < 10 kW/m; No Data	5
2	> 10 kW/m	10

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	**0**
2	10m < 20m (5.5-10.9)	**10**
3	20m < 30m (10.9-16.4)	**0**
4	30m < 40m (16.4-21.9)	**0**
5	40m < 50m (21.9-27.3)	**0**
6	50m < 75m (27.3-41)	**0**
7	75m < 85m (41-46.5)	**0**
8	85m < 100m (46.5-54.7)	**0**
9	100m < 200m (54.7-109.4)	**0**
10	>200m (>109.4)	**0**

Attribute: Substrate

Ref.	Classification	Score
1	Rock	10
2	Gravel	7
3	Sand	8
4	Cobble	5
5	Mud	8

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	7
4	15 NM < 20 NM	4
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	<1 NM	10
2	1 NM < 2 NM	9
3	2NM < 3 NM	8
4	3 NM < 4 NM	7
5	4 NM < 5 NM	6
6	5 NM < 6 NM	5
7	6 NM < 7 NM	4
8	7 NM < 8 NM	3
9	8 NM < 9 NM	2
10	9 NM < 10 NM	1
11	> 10 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	9
3	6 NM < 9 NM	8
4	9 NM < 12 NM	4
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

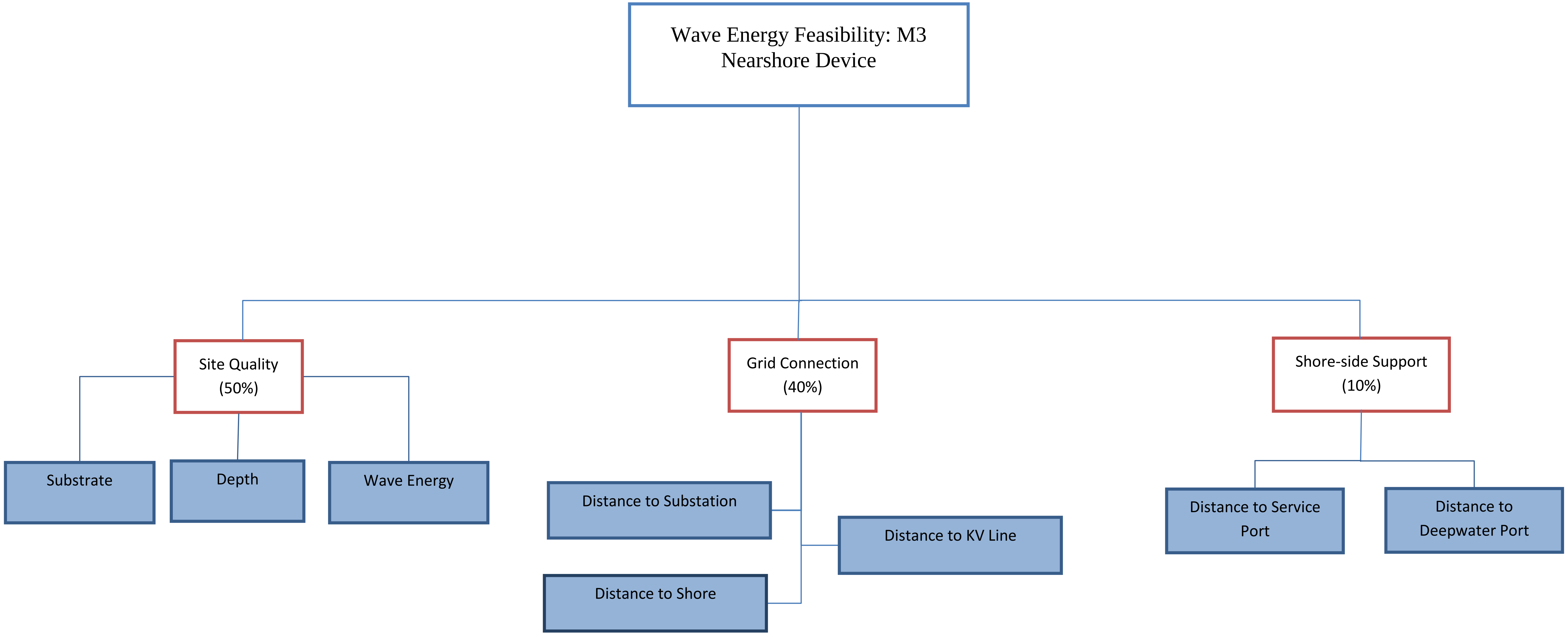
Attribute: Distance to Service Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 20 NM	8
4	20 NM < 30 NM	7
5	30 NM < 40 NM	6
6	40 NM < 50 NM	5
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

Resources: Batten 2013, EPRI 2005, Klure 2013, Morrow 2013, Murray 2013, OWET 2010, Ozkan-Haller 2013, Rezza 2013



Model: **Wave Energy Feasibility: M3 Nearshore Device in Economically Constrained Environment**

Key:

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest National Laboratory Parametrix

Model Specifications – M3 Nearshore Wave Energy Device

Background

The economically-constrained M3 nearshore wave energy device feasibility model evaluates the feasibility of siting the M3 Delos-Reyes Morrow Pressure Device device in a full-scale but pre-commercial context. In this context, M3 devices do not generate sufficient revenue to overcome the importance of proximity to shore-side services and infrastructure. The suitability scoring reflects the financial importance of proximity to shore and a potential grid connection. The M3 Delos-Reyes Morrow Pressure Devices are completely submerged and mounted on the seabed.

Suitability Evaluation

The three sub-models that determine nearshore wave energy feasibility are site quality, grid connection, and shore-side support.

The Site Quality Sub-model considers the wave resource, water depth, and the suitability of the seafloor substrate for anchoring or mounting devices.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line. While connecting to a sub-station is not anticipated to be a necessity for most pre-commercial installations, it is a relevant factor for site expansion opportunity.

The Shore-side Support Sub-model evaluates the ability of existing shore-side resources to satisfy wave energy developers' needs for access to a deepwater port for device installation, and access to a service port for operations and intermittent maintenance.

Site Quality Sub-Model

Attribute: Mean Annual Wave Power Density

Ref.	Classification	Score
1	1 < 10 kW/m; No Data	5
2	> 10 kW/m	10

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	**0**
2	10m < 20m (5.5-10.9)	**9**
3	20m < 30m (10.9-16.4)	**10**
4	30m < 40m (16.4-21.9)	**9**
5	40m < 50m (21.9-27.3)	**0**
6	50m < 75m (27.3-41)	**0**
7	75m < 85m (41-46.5)	**0**
8	85m < 100m (46.5-54.7)	**0**
9	100m < 200m (54.7-109.4)	**0**
10	>200m (>109.4)	**0**

Attribute: Substrate

Ref.	Classification	Score
1	Rock	10
2	Gravel	7
3	Sand	8
4	Cobble	5
5	Mud	8

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	7
4	15 NM < 20 NM	4
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	<1 NM	10
2	1 NM < 2 NM	9
3	2NM < 3 NM	8
4	3 NM < 4 NM	7
5	4 NM < 5 NM	6
6	5 NM < 6 NM	5
7	6 NM < 7 NM	4
8	7 NM < 8 NM	3
9	8 NM < 9 NM	2
10	9 NM < 10 NM	1
11	> 10 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	9
3	6 NM < 9 NM	8
4	9 NM < 12 NM	4
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

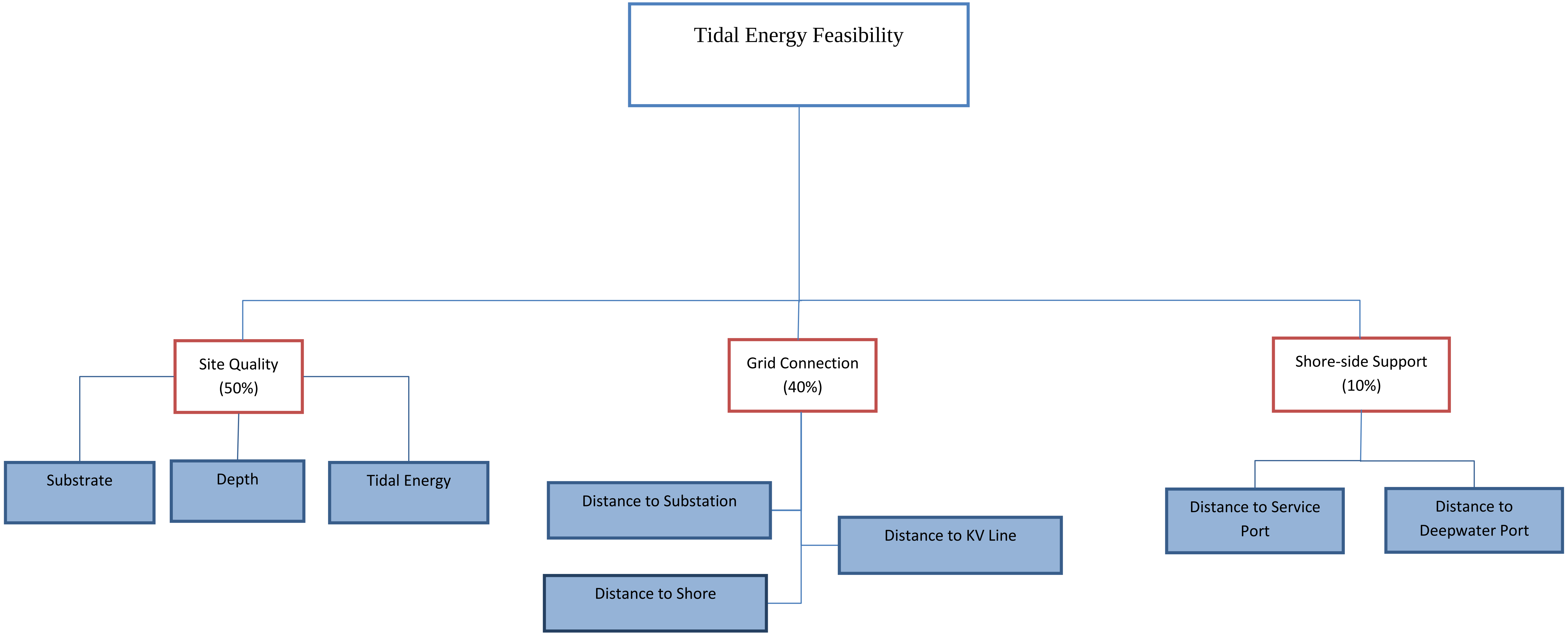
Attribute: Distance to Service Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 20 NM	8
4	20 NM < 30 NM	7
5	30 NM < 40 NM	6
6	40 NM < 50 NM	5
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

Resources: Batten 2013, EPRI 2005, Klure 2013, Morrow 2013, OWET 2010



Model: **Tidal Energy Feasibility: Economically Constrained Environment**

Key:

Attribute

Sub-Model (Weighting)

Model Link

Marine Renewable Energy Suitability Analysis for Washington State

Developed by: Pacific Northwest NATIONAL LABORATORY Parametrix

Model Specifications – Tidal Energy

Background

The economically-constrained tidal energy device feasibility model evaluates the feasibility of siting devices in a full-scale but pre-commercial context. In this context, tidal energy devices do not generate sufficient revenue to overcome the importance of proximity to shore-side services and infrastructure. The suitability scoring reflects the financial importance of proximity to shore and a potential grid connection.

Tidal exchange velocities greater than 5 knots (2.5m/s) are generally required for economically viable energy generation. Consequently, tidal energy development would occur in nearshore areas where current speed is accentuated by landform constrictions.

This analysis focuses on devices with horizontal axis and vertical axis/cross-flow turbines. These devices are gravity mounted onto or anchored to the seabed with a penetrating anchor or pile, which limits installation depth to 50-60m, or a gravity foundation, which has greater depth feasibility. Mooring is either flexible or rigid. We considered a surface clearance of 5 m above the device to be minimum. In shipping channels, an additional 15 - 25m of surface clearance is required (Polagye et al. 2011).

Suitability Evaluation

The three sub-models that determine tidal energy feasibility are site quality, grid connection, and shore-side support. The Site Quality Sub-model considers the tidal resource, water depth, and the suitability of the seafloor substrate for anchoring or mounting devices.

The Grid Connection Sub-model assesses the distance that a power cable would have to traverse , considering proximity, based on the Euclidean distance, to shore from the project site, and distance from shore to an existing onshore substation, and the closest transmission line or kilovolt (KV) line. While connecting to a sub-station is not anticipated to be a necessity for most pre-commercial installations, it is a relevant factor for site expansion opportunity.

The Shore-side Support Sub-model evaluates the ability of existing shore-side resources to satisfy tidal energy developers' needs for access to a deepwater port for device installation, and access to a service port for operations and intermittent maintenance.

Site Quality Sub-Model

Attribute: Mean Power Density

Ref.	Classification	Score
1	0 < 0.5 kW/m^2	0
2	0.5 < 1.0 kW/m^2	4
3	1.0 < 2.0 kW/m^2	8
4	2.0 < 3.0 kW/m^2	10
5	> 3.0 kW/m^2	10

Attribute: Depth in Meters (fathoms)

Ref.	Classification	Score
1	0m < 10m (0-5.5)	**0**
2	10m < 20m (5.5-10.9)	**6**
3	20m < 30m (10.9-16.4)	**8**
4	30m < 40m (16.4-21.9)	**9**
5	40m < 50m (21.9-27.3)	**10**
6	50m < 75m (27.3-41)	**8**
7	75m < 85m (41-46.5)	**4**
8	85m < 100m (46.5-54.7)	**3**
9	100m < 200m (54.7-109.4)	**2**
10	>200m (>109.4)	**1**

Attribute: Substrate

Ref.	Classification	Score
1	Rock	7
2	Gravel	6
3	Sand	5
4	Cobble	7
5	Mud	5

Grid Connection Sub-Model

Attribute: Distance to Substation

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	6
3	10 NM < 15 NM	3
4	15 NM < 20 NM	2
5	> 20 NM	1

Attribute: Distance to Shore

Ref.	Classification	Score
1	<1 NM	10
2	1 NM < 2 NM	9
3	2NM < 3 NM	8
4	3 NM < 4 NM	7
5	4 NM < 5 NM	6
6	5 NM < 6 NM	5
7	6 NM < 7 NM	4
8	7 NM < 8 NM	3
9	8 NM < 9 NM	2
10	9 NM < 10 NM	1
11	> 10 NM	1

Attribute: Distance to KV Line

Ref.	Classification	Score
1	0 <3 NM	10
2	3 NM < 6 NM	8
3	6 NM < 9 NM	5
4	9 NM < 12 NM	3
5	12 NM < 15 NM	2
6	> 15 NM	1

Shore-side Support Sub-Model

Attribute: Distance to Service Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 15 NM	8
4	15 NM < 20 NM	7
5	20 NM < 25 NM	6
6	25 NM < 30 NM	5
7	30 NM < 50 NM	3
8	>50 NM	1

Attribute: Distance to Deepwater Port

Ref.	Classification	Score
1	<5 NM	10
2	5 NM < 10 NM	9
3	10 NM < 20 NM	8
4	20 NM < 30 NM	7
5	30 NM < 40 NM	6
6	40 NM < 50 NM	5
7	50 NM < 100 NM	4
8	100 NM < 150 NM	3
9	150 NM < 200 NM	2
10	>200 NM	1

Resources: Gooch 2009, Johnson 2013, Marquis 2013, OWET 2010, Polagye et al. 2011, Polagye 2013

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