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Marine energy resource characterization, and classification in the United States

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Abstract—**Comprehensive, detailed and reliable data on marine energy resource characteristics is essential for advancing the marine renewable energy industry. In this paper, we showcase the U.S. Department of Energy's resource characterization and assessment project. This multi-year project, conducted by three national labs, is delivering data and results designed to reduce the uncertainty, risk, and cost of marine energy technology. Over its first three years this project has: 1) completed high-resolution, long-term regional wave hindcasts for the U.S. west coast, east coast, and Alaska, 2) completed high-resolution tidal models of five top-ranking tidal energy sites, 3) completed resource measurements following International Electrotechnical Commission (IEC) technical specifications at four wave energy sites and four tidal energy sites, and 4) developed wave classification schemes. The project has been guided by an international steering committee composed of industry partners and academic experts. As the project moves toward completion the team will: complete high-resolution modelling for all U.S. coastal waters, complete resource measurements at top-ranking sites, refine the national resource assessments, propose classification schemes to the IEC standards body, and upgrade the Marine and Hydrokinetic (MHK) Atlas to make the project's data public and accessible. These data and tools can be used for: device design processes for technology developers, economic assessments for project developers, energy assessments (power supply and energy portfolio diversification) for regional planners and policy makers, operational reliability and economic assessments for utilities and investors, and baseline data for environmental impacts studies needed by regulatory agencies.**

Keywords— **Classification schemes, resource assessment, resource measurement, resource modelling.**

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I. Introduction

THE wave and tidal industry is at an early stage of development and has the potential to play a significant role in diversifying the world's energy portfolio. However, efficiently and reliably converting energetic tidal and wave resources into usable energy faces inherent challenges, including:

a) the unique physics and engineering problem of harnessing energy from ocean waves and tidal currents

b) the complex physics and statistics of these resources (forcing over broad ranges of temporal and spatial scales, including rogue and large-storm waves; and the large and stochastic forces associated with turbulence)

c) the logistical challenges of installing and operating technologies in the energetic and corrosive marine environment

d) the permitting process can be expensive and time-consuming, due to extensive data collection requirements and a lack of knowledge of the potential environmental impacts of MHK technologies

e) a wide range of site-specific design constraints (e.g., resource intensity, water depth, bottom composition, competing-use constraints, environmental concerns, etc.)

To overcome these challenges, the wave and tidal community needs comprehensive, accurate, and well-organized public data on resource characteristics, especially where early projects are likely to be deployed. Accurate high-resolution resource model hindcasts, validated with measurements, are needed to improve the coverage, resolution and accuracy of resource characterization and assessments at regional and local

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scales, for device and array design, to improve device efficiency, and to reduce risks posed by extreme conditions. Resource maps and data catalogues that include the data from these modelling and measurement efforts are needed to identify the best project sites (hot spots) and to identify and mitigate risks at those sites. Classification systems, like those used in the wind industry, need to be incorporated into wave and tidal industry standards to streamline project development, technology design and manufacturing.

The U.S. Department of Energy's (DOE) resource characterization and assessment efforts are designed to address the above challenges in a coordinated and strategically focused project by combining the institutional resources of the three DOE national labs at the forefront of U.S. wave and tidal energy research: the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL). The project holds quarterly calls with a steering committee of international experts and U.S. industry representatives to solicit guidance on key project decisions, and to keep the community informed on project progress. Section II describes the background and motivation from which the project emerged. The project is organized around four primary activity areas: resource measurements (section III), resource modelling (section IV), resource characterization (section V) and resource classification (section VI). Each lab leads one activity area and NREL serves as the lead for the project as a whole. All of these activities are conducted with careful attention to best practices and methods recommended by the International Electrotechnical Commission's (IEC) Technical Committee (TC) 114.

II. Project Background

The Resource Characterization project, which began in 2016, is motivated by a recognition that detailed resource data is critical to the success of the marine energy industry. Resource data, e.g., annual average power density, is extremely important to a multitude of stakeholders, e.g., the DOE, regional energy planners, and energy project and technology developers, who need to assess the opportunities for developing energy resources. The geographic distribution of resource data, its temporal distribution on multiple scales (annually, seasonally and hourly), and probabilistic distribution, including statistics on extreme values, are important to characterize and assess opportunities, risks and constraints for project development and energy conversion technology design.

National wave and tidal resource assessments provided estimates of the total national energy resource and its geographical distribution, which was disseminated in the MHK ATLAS [1], [2]. As *reconnaissance* level assessments, these studies relied on coarse-resolution model hindcasts to derive average annual estimates of the *theoretical* energy resource. These models lacked the resolution to characterize and assess the resource at the higher level of resolution and accuracy required for project development and energy conversion technology design. In addition, a review by the National Academy of Sciences identified several shortcomings of these resource assessments [3].

TABLE I
MEASUREMENT SITES, STATUS, AND SCHEDULE. WAVE SITES ARE BLUE, AND TIDAL SITES ARE ORANGE.

Site	Status	Position	Depth
FY16			
Oregon: Lakeside and Reedsport	**Buoys removed** April 2018.	43.586N, 124.290W 43.760N, 124.225W	85m 45m
Maine: Western Passage	**Operations complete.**	44.92N, 66.99W	60m
FY17			
California: Fort Bragg	**Buoy removed** September 2018.	39.368N, 123.911W	125m
Alaska: Kodiak	**Operational.** Exploring collaboration to extend beyond 2019.	57.479N, 151.695W	90m
Washington: Tacoma Narrows, Rosario Strait, Bellingham Channel	**Operations complete.**		
FY19			
Alaska: Cook Inlet	**Planned: Summer 2019.** Turbulence, spatial variability.	60.72N, 151.43W	40m
FY20			
Puerto Rico	**Planned: January 2020.**	18.56N, 66.43W	100m
N. Carolina: Cape Hatteras	**Planned: April 2020.**	35.19N, 75.51W	20m

There were several parallel activities occurring in 2016 that time that contributed to defining the scope of this project:

1) A model test-bed study demonstrated a best-practice for modelling of potential wave energy project sites [4]. This study showed that high-resolution third-generation wave model hindcasts meeting the International Electrotechnical Commission (IEC) requirements for feasibility level assessments provided significantly more accurate predictions of wave energy resource parameters than those derived from reconnaissance level hindcasts supporting the MHK Atlas.
2) An early market site characterization project demonstrated that identifying and ranking sites that are likely to see early deployment of wave and tidal technology is possible, but that the details of these rankings depend on the quality of the data that goes into them and the assumptions that determine the relative weighting of the ranking criteria [5], [6]. In other words, while the rankings provided in these "hot-spots reports" effectively identify many of the top U.S. wave and tidal energy sites, the detailed ranking of those sites relative to one another is dependent on the data quality and the details of the ranking system.
   The hot-spots reports also demonstrated that while tidal resource data was relatively high-resolution and could be used to identify specific project sites, the publicly available wave resource data was of insufficient resolution to identify specific wave sites. On the other hand, there are several sites where measurements have shown that the publicly available tidal resource assessments misrepresent the resource intensity [2], [7], [8]. These results indicated that higher resolution wave models were needed to identify project sites, and higher-accuracy (validated)

Fig. 1. Two Datawell Waverider buoys prior to deployment off the coast of Oregon. *Photo: Frank Spada, Integral Consulting*

tidal models were needed at several sites to accurately quantify project opportunities.

3) The advanced turbulence measurements project had successfully demonstrated methods for measuring turbulence using acoustic Doppler velocimeters positioned at tidal turbine hub-heights on compliant moorings. The key innovation in this work was in demonstrating that inertial motion measurements can be used to reduce motion contamination of velocity measurements made from compliant moorings [9].
4) Finally, the IEC TC 114 had recently published technical specifications that formalized international consensus on the methods for quantifying wave and tidal resource opportunities [10], [11]. These specifications provide recommendations on key parameters (statistics) that should be estimated for resource characterization and assessment. They also define the three different levels of assessment, namely *reconnaissance*, *feasibility* and *design*, and requirements for hindcast models and measurements used to generate data sources to estimate these resource parameters. However, these technical specification had been applied at a limited number of locations, and their pathway to acceptance as full 'standards' required refinement based on user feedback.

Each of these activities pointed to the limitations of existing data, and/or demonstrated improved methods for obtaining the data that is needed to advance a nascent U.S. wave and tidal industry. Around this same time there was also a growing consensus within the U.S. wave industry, at DOE, and within the U.S. National Labs that marine energy classification schemes, like those for wind, would be valuable to streamlining wave and tidal project development and technology design. It was also clear that parameters for these classification schemes, like the MHK Atlas, should be based on the best available wave and tidal resource data generated by long duration (32-year) high-resolution model hindcasts or in-situ measurements.

It was from this context of a clear need for high quality data, and the recent demonstration of tools to deliver it that the U.S. DOE and its National Labs collaborated to create this centrally organized project.

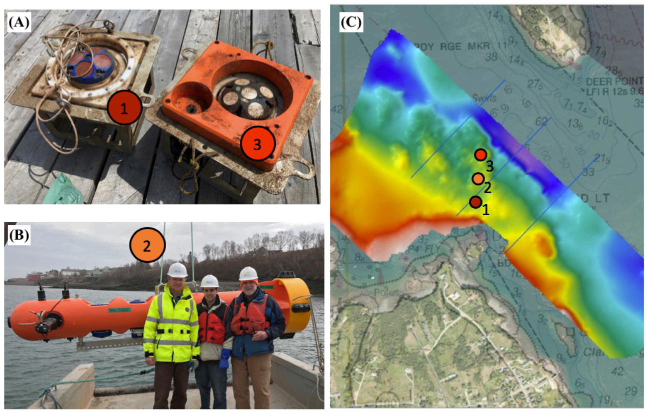

Fig. 2. Two ADPs (A), and a StableMoor buoy (B) prior to deployment at sites in the Western Passage of Maine (C). *Photos: Levi Kilcher, NREL*

III. Resource Measurements

The resource measurements activity has three primary objectives: 1) to provide model validation data where existing publicly available data is sparse, 2) to measure the resource at early market sites that lack existing public data (i.e., sites that are expected to see the first tidal or wave projects), and 3) to provide high-fidelity turbulence statistics at tidal energy sites for classification schemes. Site selection, informed by the above objectives, began with a data-needs assessment of the sites identified in the hot-spots reports.

A. Wave Measurements

The fact that publicly available wave resource data is inadequate for detailed site selection (i.e., it is currently relatively low resolution) means that wave measurement siting was driven primarily by a data-needs assessment to meet objective 1 (model validation). This needs assessment considered the spatial distribution and water depth of publicly available directional wave spectra. Regions that lacked this data at regionally relevant water depths were selected for measurement (Table I). Datawell Waverider buoys were deployed at the selected sites (Fig. 1), and the data from these measurements has been made available in real-time in collaboration with the Coastal Data Information Program (http://cdip.ucsd.edu). The data from these measurements are being used to validate the high-resolution model simulations in this project.

A summary of the rationale that leads to the wave measurement schedule in Table I is as follows: Hawaii is a top-ranking wave hot-spot, but it already has several high-quality directional wave-spectra measurements – including at the Hawaii National Marine Renewable Energy Center's *Wave Energy Test Site*. Therefore, Hawaii was not selected as a site for measurements under this project. The U.S. pacific northwest, another top-ranking region composed of Washington state, Oregon, and northern California, lacked recent shallow-water measurements which motivated the selection of the shallow-water sites at Lakeside and Reedsport Oregon. The Fort Bragg, California, site was selected to fill the relatively large (~300 km) spatial gap in directional-spectra

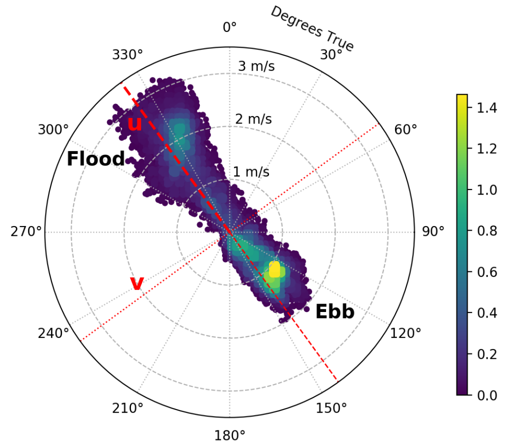

Fig. 3. A 'scatter-histogram' joint velocity and direction probability distribution from the Western Passage of Maine. The colors correspond to a traditional joint probability distribution, of u and v velocity components (color-scale units of $(m/s)^{-2}$).

measurements between Cape Mendecino and Point Reyes California.

The Kodiak buoy site was selected because there were no directional-spectra wave measurements that were both: within 100 km of the coast and broadly exposed to the Pacific Ocean. The data from that buoy, therefore, is particularly valuable for model validation because there are no comparable wave measurements within several hundred kilometres. For this reason, NREL is working to collaborate with the Alaska Ocean Observing System to extend the life of this buoy beyond 2019. The Puerto Rico site was selected to measure directional wave-spectra there with exposure to waves from the North Atlantic Ocean. The Cape Hatteras buoy has been sited to measure the resource at this top-ranking East Coast wave site.

B. *Tidal Measurements*

For tidal sites, the fact that models had been shown to misrepresent the resource indicated that the hot-spots rankings needed to be interpreted carefully. Fortunately, the top-three tidal hot-spots – Cook Inlet, Alaska; the Western Passage, Maine; and several sites in Puget Sound, Washington – were clear leaders in the site-rankings even when accounting for uncertainty in the resource data. Furthermore, these sites did not possess the kinds of detailed hub-height resource and turbulence measurements that had been demonstrated previously [9].

It was therefore clear that measurements should be made at these locations to provide high quality data for these promising sites (Table I). Other sites where no measurements existed to validate the tidal models may be prioritized in future work based on heuristic assessments of the market opportunity and the potential resource uncertainty. The locations where resource models had been demonstrated to be inconsistent with measurements are the subject of refined modelling efforts (discussed below).

Tidal measurements from the Western Passage, Maine, are presented here as an example of the type and quality of tidal measurements collected under this project (Fig. 2).

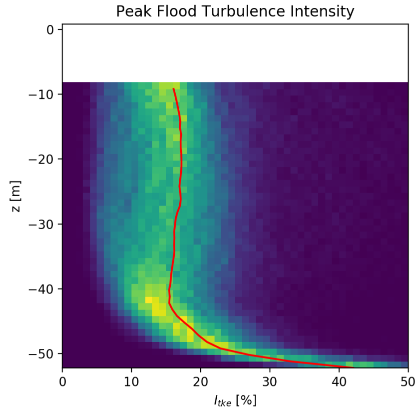

Fig. 4. Joint probability-distribution of turbulence intensity and depth during peak flood (u > 1.8 m/s) from ADP #3 in Fig. 1. The average turbulence intensity profile is shown in red. The upper 8 meters are masked because the data there are contaminated by acoustic sidelobe interference from the water surface.

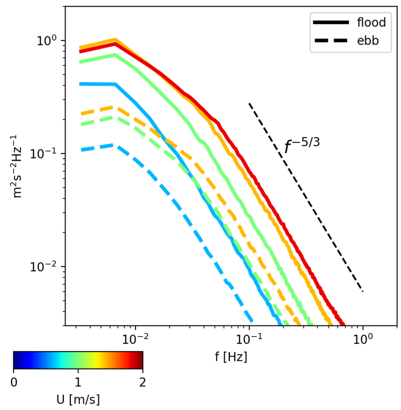

Fig. 5. Along-beam spectra from an upward-looking ADP in Western Passage. Warmer colours denote larger mean velocity.

The measurements are designed to adhere to IEC TC114 technical specifications in providing high-quality resource-model validation data. The velocity-direction joint probability distribution, which is required by the IEC tidal resource assessment technical specification, shows a clear ebb-flood asymmetry: flood velocities typically exceed 2 m/s but ebb velocities are usually less than 1.5 m/s (Fig. 3). This figure also shows that the tidal velocities oscillate on a 'principal axes' oriented at 322° degrees True.

The tidal measurements in this project utilize a mix of instrumentation and deployment platforms. In the Western Passage, we positioned two upward-looking Acoustic Doppler Profilers (ADPs) at positions 1 and 3 (600 kHz and 500 kHz, respectively), and a StableMoor buoy equipped with upward and downward looking ADPs, and two ADVs was deployed at position 2 (Fig. 1). The ADVs heads were placed at the ends of a horizontal 'wing' that positioned the two instruments 1.5 m apart laterally to the flow. This pairing can then be used to estimate the lateral spatial coherence of the tidal velocities, which has been shown to be an important inflow parameter for estimating loads on wind turbines [12]–[14]. The downward looking ADP on the StableMoor is configured to measure the platform motion ('bottom-tracking'), to aide in correcting the ADV velocity measurements as described in [9], [15].

TABLE II
REGIONAL WAVE MODELLING SCHEDULE

Region	Lab	Status
U.S. West Coast	PNNL	Complete
Alaska	PNNL	Complete
U.S. East Coast	SNL	Complete
Gulf of Mexico	SNL	*2019*
Hawaiian Islands	PNNL	*2019*
Puerto Rico and U.S. Virgin Islands	SNL	*2020*
U.S. Pacific Islands	PNNL	*2020*

The StableMoor was tethered at 12 m above the bottom, which is the approximate hub-height of many tidal energy devices.

A new generation of ADP is now commercially available that has significantly better signal-to-noise characteristics compared to earlier models [16]. These systems allow users to measure turbulence statistics – including turbulence intensity (Fig. 4) and along-beam spectra (Fig. 5) – from the same type of system that is typically used for resource assessments. Fig. 4 shows that the mean turbulence intensity at mid-depths is between 15 and 20%, and it also shows that the instantaneous turbulence intensity at these depths varies widely between 5% and >30%. The latter fact (especially the highest values of turbulence intensity) is an important and potentially under-appreciated detail that is important for accurately modelling device loads due to turbulence. Also note that the high values of $I_{tke} = (2*tke)^{(1/2)}/U$ are due to the low values of mean velocity (*U*) near the bottom, and do not indicate rapidly increasing turbulent kinetic energy (*tke*) as you approach the bottom.

Measurements of spectra are also of great importance to accurate estimates of loads from device simulation tools [17]. Figure 5 shows that the flood turbulence (solid lines) is 2-3 times as energetic as the ebb turbulence (dashed lines) at the same flow speed (same colors). This is just one example of how much variability exists in turbulence statistics, and therefore how important a more detailed understanding of hub-height turbulence is for device design.

The spectra are the primary input variable to inflow simulation tools such as TurbSim [18]. The data collected under this project will be used to better understand the variability of turbulence statistics at some of the most promising U.S. tidal energy sites. As the international community continues to build a database of these statistics, we plan to provide inflow simulation tools that are representative of this variability and can eventually be incorporated into classification schemes and IEC design standards.

IV. RESOURCE MODELLING

The resource modelling activity is led by PNNL, but in collaboration with SNL to leverage the institutional knowledge and computing resources of both labs (Table II). Tidal modelling was also supported by Georgia Tech, which led the national tidal energy resource assessment effort [19].

TABLE III
TIDAL MODELLING SCHEDULE.

Region	Lab	Status
Western Passage, Maine	PNNL	Complete
Puget Sound, Washington	PNNL	*2019*
Cook Inlet, Alaska	PNNL	*2019*
Long Island Sound	GTech*	Complete
Portsmouth Harbor	GTech*	Complete
Cape Cod Canal	GTech*	Complete
Delaware Bay	GTech*	Complete
Key West	GTech*	Complete

*: Models completed by GTech were completed under the separately funded 'Tidal Gaps Analysis' project.

C. Wave Modelling

The primary objectives of the wave models are to provide data that provides full coverage offshore, including nearshore regions, provides sufficient high-resolution to identify specific project sites, and to provide an accurate data source from which a broad range resource parameters can be generated to characterize the resource, to build classification systems, and upgrade the MHK Atlas. These regional model hindcasts span 32 years, extend the model domain from shoreline to the U.S. economic exclusion zone (EEZ), and utilize state-of-the-art third-generation wave physics packages for wave source terms. They use unstructured grids that have a spatial resolution of 200 m in the shallowest areas.

Previous national wave resource models were much lower resolution (5-7 km) [1]. Data from the new models – annual and monthly averages of all six IEC wave resource parameters – are being added to the MHK Atlas as the data becomes available. The first regions (the U.S. West Coast and Alaska) are available as of April 2019. Further details of the wave modelling work, including figures that compare the spatial resolution of the new models to previous works, can be found in a companion paper [20].

D. Tidal Modelling

The tidal modelling conducted under this project is being completed by PNNL. These models are co-located with the tidal measurements in Table I. Preliminary versions of the models have been used to refine detailed measurement siting. After measurements are collected, model validation studies are being conducted to improve resource estimates at these promising tidal energy sites (forthcoming publications). These tidal models also utilize unstructured grids that have been designed to focus on the most energetic tidal energy sites in a region [21], [22]. These high-resolution models are being used to aide detailed measurement site selection, and to improve our understanding of tidal energy opportunities in these promising regions. These model results will be incorporated into the MHK Atlas in 2020.

In parallel to the tidal modelling work under this project, DOE also supported NREL and Georgia Institute of Technology (GTech) in the "Tidal Gaps Analysis" project. The primary focus of this work was to identify locations where the resource assessment had discrepancies with measurements. The second task was to prioritize and run refined tidal models at several locations where discrepancies were found (Table II). Tidal power density, and mean current speed data from the Tidal Gaps Analysis project have been incorporated into the MHK Atlas (the earlier data has been replaced).

V. Resource Characterization

An overarching goal for this project is improving the scope, accuracy and resolution of US wave and tidal energy resource characterizations. We define *resource characterization* as *the process of parameterizing and mapping the attributes of a marine energy resource using a set of resource parameters or metrics derived from the collection, processing and parameterization of met-ocean data.* Resource characterization enables *resource assessment,* which we define as *the appraisal or valuation of a marine energy resource (national, regional, or site) to enable the determination of a marine energy resource's ability (potential) for marine energy conversion*. As resource assessment by this definition depends on the region of interest, our project scope is generally limited to resource characterization.

For example, the main attribute of an energy resource that characterizes the resource's potential opportunity for energy conversion is the theoretical power density. This opportunity for wave resources is characterized (parameterized) using the IEC resource parameter J (W/m), which is calculated as:

$$J = \rho g \sum_i S_i C_{g,i} \Delta f_i \qquad (1)$$

where ρ is the sea water density, $C_{g,i}$ is the group velocity at frequency i, and $S_i \Delta f_i$ is the total variance at frequency f_i [10]. The independent variables on the right-hand-side of (1) are calculated from collected data sources derived from observations, e.g., buoy measurements, or validated model hindcasts.

For tidal resources, the available annual mean power density, APD (kW/m²), characterizes the resources potential, and is estimated as

$$APD = \frac{1}{2}\frac{1}{N}\rho \sum_{j=1}^{N} U_j^3 \qquad (2)$$

where j is the index of the model time step increment or long-term output interval, U_j is the respective velocity, and N is the total number of time-step increments. However, as pointed out by Garrett and Cummins and others, there are hydrodynamic constraints that may limit this theoretical power density [23].

As described above, this project relies mainly on validated high-resolution regional wave model hindcasts, which are accepted by IEC technical specifications and have been demonstrated to provide accurate data sources for estimating IEC wave resource parameters, including extremes [4], [24]. Conversely, while model hindcasts accurately resolve the theoretical power density for tidal resources, some important IEC tidal resource parameters, like turbulence intensity, are not accurately resolved, and, therefore, must be estimated from site measurements.

Table IV
Wave Resource Parameters.

Parameter	References
Power, Power density, J	IEC [4]
Significant wave height, H_s	IEC [4]
Energy Period, T_e	IEC [4]
Spectral width, ϵ_0	IEC [4]
Directionality coefficient, d	IEC [4]
Direction of max power, θ	IEC [4]
Peak period band, n	Ahn et al. [24]
Monthly variability, MV	Haas et al. [25]
R. risk ratio, $H_{s(50)}/H_{s(mean)}$	Neary et al. [26]

Table IV lists some of the resource parameters that have been proposed to characterize wave energy resources, including those recommended by the IEC standard [10], and those introduced in this project to improve the fidelity of wave resource characterization [25]–[27]. Annual average values of wave power among different wave sites, and different wave climates, are typically used to characterize, compare and assess opportunities for energy conversion. However, it is widely recognized that this measure of opportunity should be balanced with other resource parameters that characterize the quality of the energy resource, e.g., ϵ_0, d, MV, constraints on energy conversion, e.g., n, and project risks, e.g., $H_{s(50)}/H_{s(mean)}$.

Energy planners, project developers and designers need to know the range and distribution of these resource parameters, how these values are distributed geo-spatially, temporally (e.g., monthly variability), and probabilistically (e.g., mean, large quantiles, n-year return period values). On-line maps of these parameters, e.g., the MHK Atlas, will be upgraded to streamline dissemination of geo-spatial information, and data will be catalogued to generate time series (temporal maps) and probabilistic maps, e.g., cumulative frequency distributions of individual parameters or joint probabilities, e.g., scatter plots showing the frequency of occurrence of sea states and the energy distribution among sea states (H_s, T_e).

VI. Resource Classification

The resource data generated in this project by measurements and model hindcasts will be used to build marine energy classification systems like those developed for the wind industry, e.g., the wind resource classification system [28] and wind turbine (conditions) classification system [29]: wave and tidal energy resource classification systems that, like [28], streamline resource assessment; and wave and tidal conditions classification systems, like [29], to streamline WEC and TEC design, product line development and manufacturing. These classification systems, include a beta-version wave energy resource classification system for the U.S. [25], and conceptual classification systems for tidal energy resource, wave conditions, and tidal conditions, as described in [30].

The type certificates that come out of classification and standards are critical to project developers for demonstrating to financial institutions and investors that their technology adheres to robust performance and manufacturing standards. This, in turn, is expected to increase investor confidence and reduce interest rates, thereby increasing project viability.

These considerations have motivated the U.S. wave and tidal industry to engage heavily in IEC TC114, and to advocate for public investment in the development of classification schemes. Now that the U.S. has classification schemes that are consistent with U.S. resource and market needs, the next step is to begin collaborating with the international community via the IEC standards process to refine the classification schemes for global markets. Eventually, we plan to propose that classification schemes become a part of IEC TC114 design, resource assessment, and power performance standards. Details on the current status of U.S. classification work, and the proposed wave and tidal classes can be found in companion papers [24], [30].

VII. Conclusion

The U.S. resource characterization and assessment project brings together the resources and expertise of three national labs to advance the state-of-the-art in tidal and wave energy resource characterization methods and products. The project's centralized structure allows the labs to pool ideas, resources, and expertise to deliver high-quality products that include a wide-range of perspectives and approaches. All of this work is tightly aligned with the IEC TC114 technical specifications; the project both utilizes and provides feedback to the IEC documents, and the project's leaders are active members of IEC TC114.

The primary outputs of the project are: public resource measurement data, public model data, and publications. The publications include journal papers and technical reports on the topics of classification, model validation, resource measurements, and regional resource assessment. Public data products will continue to be made available on the MHK Data Repository, via the MHK Atlas, and wave measurement data is available on cdip.ucsd.edu servers.

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