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Marine energy classification systems: Tools for resource assessment and design

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***Abstract*— Conceptual and beta-version *resource* classification and *conditions* classification systems modelled after those for wind, are described for wave and tidal resources in the United States. *Resource* classification systems are designed to support resource assessment studies for marine energy planning and projects. *Conditions* classification systems are designed to streamline and reduce costs for design, device-type certification, product-line development and manufacturing. Design requirements and steps in building these marine energy classification systems are highlighted, including parameter selection, class delineation, matrix layout and mapping. Best available data sources for computing classification parameters include model hindcast outputs and field measurements. Like wind, these two distinct types of classification systems, *resource* and *conditions*, are powerful tools to support project development, device design and manufacturing; but these benefits are only fully realized through codification of these classification system tools within international standards and certification.**

***Keywords*—wave and tidal energy resource, classification, design load conditions, standards, certification.**

I. INTRODUCTION

THE success of wind classification systems has motivated interest in analogue classification systems for the wave and tidal energy industry. Wave and tidal energy *resource (project)* classification systems, designed to support the appraisal of the resource in terms of opportunity for energy generation based on power density as well as project constraints and risks, would serve as resource assessment tools that facilitate siting, project scoping studies and regional energy planning. *Conditions (device)* classification systems, by establishing standard classes for the limiting environmental conditions for device design, would streamline and reduce costs for design, device-type certification, product-line development and manufacturing; while minimizing technical and financial risks for investors.

We review wind *resource* and *conditions* classification concepts to highlight important attributes of these systems, their design intentions (requirements), the methods and assumptions in building them, and how they are incorporated within international standards and certification. We then present analogue resource and conditions classification systems for marine energy resources at different stages of development, from conceptual prototypes (strawmen) to preliminary beta versions that can be tested and adjusted as industry knowledge and experience are gained.

II. WIND ENERGY CLASSIFICATION

A. *Wind resource classification*

Wind *resource* classification systems include the wind resource classification system developed for the US [1], Figure 1, and Europe [2]. These classification systems are the basis for wind resource maps and atlases that have supported national and regional energy planning and numerous project development studies at reconnaissance and feasibility stages [3].

The main classification parameter for these resource classification systems is wind power density (W/m^2), derived from wind observations at thousands of sites as a measure of project *opportunity* to generate power. The European classification system has five resource (power density) classes compared to seven for the US system. It also uses topographic condition as a second parameter to adjust for terrain roughness and orographic (Venturi) effects encountered in hills and ridges. The topographic condition is a quality measure of power density, with some topographies, e.g., open sea, having more power density than rougher topographies of the same class, e.g., sheltered terrain.

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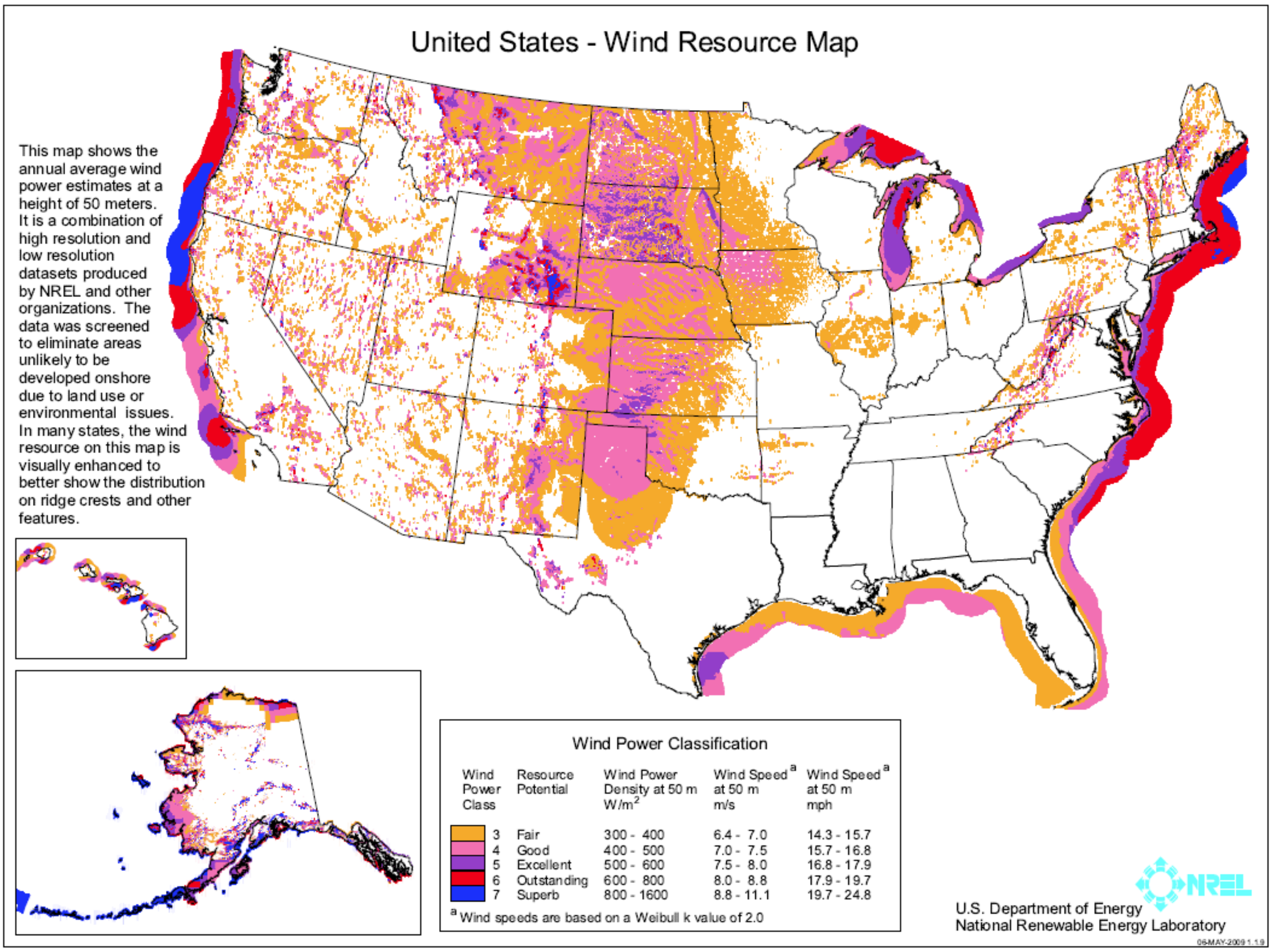

Fig. 1. Wind energy resource classification system [NREL 1986]

US resource classes 3-7 roughly correspond to the five European (open sea) resource classes and encompass the range of operating conditions for standard commercially available wind turbine power classes described in the next section. However, the rationale for delineating resource classes and sizing each power density band is not documented for either system. The bandwidth for the mid-range resource in the European system is 400-600 W/m², whereas that for the US system is 500-600 W/m². Bandwidths vary in both systems from 50 W/m² to 800 W/m², but are typically 100 or 200 W/m². Class delineations and bandwidth sizes were likely adjusted to discriminate distinct regional geo-spatial trends in the wind resource maps.

Curiously, no international standard wind resource classification system has been developed; likely because a wind resource characterization and assessment standard was never codified in the early days of the industry when characterization and assessment efforts were a priority. Although a committee draft (CD) of a new standard on site specific wind *conditions* assessment is now under development [4], its focus on wind conditions, rather than resource attributes for project development and energy planning, reflects a mature industry prioritizing improvement to device performance through improved design-level resource characterization.

B. *Wind conditions classification*

The International Electrotechnical Commission (IEC) wind turbine classification system codifies wind conditions classification within the design standard for wind turbines [5]. It is credited by experts as *streamlining the design procedure and costs for wind turbines; providing industry with something to design and build to, and significantly reducing manufacturing costs by building relatively few standard wind turbine classes compared to many bespoke wind turbines* [6].

As shown in Table I, two parameters with values representing the upper design boundaries are used to delineate nine classes of wind conditions corresponding to nine wind turbine classes: a reference wind speed, U_{ref}, (the 10-minute average wind speed with a 50-year recurrence interval) and the streamwise turbulence intensity, I_{ref}, occurring at a 15 m/s wind speed. Design load cases (DLC), for normal operation and episodic extreme wind loads, are built using just these two classification (reference) parameters, which significantly reduces design efforts. The annual average wind speed, U_{avg}, assuming a Raleigh distribution, is simply $0.2U_{ref}$. As for wind resource, other than expert judgment on what resource to design to, no clear rationale is provided for the delineation of these three power classes. The upper bound of power Class III aligns with that of a US Class 4 (*Good*) resource, whereas the upper bound for a Class II falls within US Classes 5 and 6 (*Excellent*, *Outstanding*), and that for Class I within US Classes 6 and 7 (*Excellent*, *Superb*).

TABLE I
WIND CONDITIONS (TURBINE) CLASSIFICATION [IEC 61400-1]

Power Class		I	II	III	S
U_{ref} (m/s)		50	42.5	37.5	Value specified by engineer
U_{avg} (m/s)		10	8.5	7.5	
A	I_{ref} (-) @15 m/s	0.16			
B		0.14			
C		0.12			

Although not designed to support resource assessment for project development and energy planning, wind conditions classification could be applied internationally for these applications as well because the average wind speed (power density), the main metric in the US and EU resource classes, can be derived directly from U_{ref}. Likewise, turbulence intensity could be used to assess project *risk*.

C. *Lessons from wind: summary*

Wind resource and conditions classification systems provide reference models with key ingredients needed for similar classification systems that can be used to advance the marine energy industry.

Separate wind classification systems were built and applied for resource assessment and design: resource classification systems that classify mean annual power density as a main indicator of power generation opportunity; and conditions classification that classify a reference wind speed and turbulence intensity as base (reference) parameters for calculating design load cases. However, there may be value in developing a single classification system that supports resource assessment and design if extreme conditions used for design correlate well with average annual conditions used to compute power density.

To fully realize the benefits of classification systems in supporting resource assessment, design, certification and manufacturing, classification should be formally codified within industry standards for resource assessment and design. Further, classification terminology and methods should align with these standards.

Similar approaches and methodologies can be adopted for building marine energy classification systems, including the selection of the key parameters, class delineation, matrix layout and mapping.

For energy resource classification, power density is the primary parameter, but other parameters, e.g., measures of project constraints or risks, could be introduced to build more comprehensive systems. The balance between a simple classification tool that uses only a couple of parameters and a multiple parameter one is subjective. One exceeding three parameters would likely be overly cumbersome.

Ideally, one or two classification parameters that are correlated with other resource attributes or conditions can be identified, serving as base (reference) parameters for an expanded characterization of the resource or design conditions. Other resource statistics should be computed and catalogued to allow more comprehensive characterization and assessment, and flexibility to extend classification systems as industry knowledge and experience are gained.

III. MARINE ENERGY CLASSIFICATION

The marine energy classification systems presented herein include a wave resource classification system (beta-version) and three conceptual (strawman) classification systems; one for tidal resource, one for wave conditions, and one for tidal conditions. Before presenting these classification systems, common design objectives, data sources and methods are summarized.

D. *Design goals and requirements*

Our goal is to build marine energy classification systems modelled after those reviewed for wind in the previous section, including wave and tidal resource (project) classification systems and conditions (device) classification systems.

Design requirements for these classification systems include the following:

1. Classification should be technology agnostic. This is particularly the case for wave conditions classification because there are many different wave energy converter (WEC) archetypes. Despite these technology differences, all WEC and tidal energy converter (TEC) archetypes should consider common resource attributes to assess energy generation opportunities. Similarly, while the response of different device archetypes to extreme design loads may vary, extreme hydrodynamic conditions for their design are standardized [7].
2. Classification should conform to international, consensus-based standards, such as those developed by the International Electrotechnical Commission (IEC) under Technical Committee (TC) 114: Marine energy – Wave, tidal and other water current converters. For resource classification systems, there are two relevant standards, the wave resource assessment and characterization technical specification [8] and the tidal resource assessment and characterization technical specification [9]. For conditions classification, alignment with the marine energy systems design standard, [7], is crucial. Conformance with power performance assessment standards for WEC and TEC [10], [11] is also important. These standards guide data source requirements, parameter selection and computation methods.
3. Classification systems should be based on three parameters or less but designed to be flexible to

adapt to new knowledge and experience. Additional statistics that may be useful for resource assessment and device design should, therefore, be computed. Also, it is critical that relationships between reference (base) parameters and other conditions parameters should be investigated, e.g., correlations between extreme and normal conditions.

4. Classification systems should use best available data sources for parameter estimation, including validated model hindcast outputs to provide spatial coverage over the region of interest, and measurements for parameters that cannot be accurately estimated using model outputs. The US wind classification system and wind atlas have been periodically updated using improved wind resource data sources with more accurate and extended periods of record.
5. Classification systems should be transparent and fully documented, including the rationale or expert judgment applied for parameter selection and class delineation.

E. *Methods*

The five main steps to build marine energy classification systems include:

1. Selection of classification parameters
2. Data sources and parameter computation
3. Class delineation
4. Matrix layout
5. Class mapping

For energy resource classification, power density is the obvious parameter used to assess project opportunity. However, other classification parameters could include quality measures on power density, like topographic effects for wind, or metrics to assess project risk, like turbulence intensity level. For conditions classification, the parameters selected should be those used to model the extreme design load condition, e.g., the reference wind speed and turbulence intensity; and, as base parameters, to derive the normal design load conditions.

IEC standards [8], [9] provide useful guidance on key parameters used in resource assessment and design, and on required data sources and methods for calculating these parameters. For wave and tidal resources, outputs from model hindcasts used in US resource assessments are valid data sources for computing power density for large populations of sites distributed within the region of interest. The IEC standards [8], [9] also provide requirements for model validation, spatial and temporal resolution, and accuracy at distinct levels of assessment (*reconnaissance, feasibility, and design*).

Modelled data can generally provide more extensive spatial coverage and high-resolution mapping to discriminate geo-spatial resource trends compared to point observations. However, measurements are needed to validate these models, and are important data sources themselves because large-scale hydrodynamic models often lack the fidelity and resolution to resolve other significant resource characteristics, like turbulence or extreme wave conditions.

Once classification parameters are calculated for a population of sites, classes are delineated for each parameter. Class delineation involves determining the number of classes and the bandwidth for each class. Initial delineations can be based on expert judgment or educated guesses until more knowledge and experience are gained. If parameters can be computed for a large population of sites that cover the region of interest, an objective approach is to plot the frequency distribution of classification parameter and to separate classes by standard deviation or quantiles. Class delineation can also be adjusted to discriminate distinct geo-spatial trends in resource maps. More formal cluster analysis methods, while not applied herein, could also be considered.

The matrix layout for a 1- to 2-parameter classification system is simply a table that presents the class delineations and class designations, e.g., I(A) for a wind turbine power class as shown in Table I. A 3-parameter classification system could be presented as a three-axis plot, or multiple 2-parameter tables.

Maps showing the geo-spatial distribution and extent of resource or conditions classes are valuable tools supporting resource assessment and energy planning at different levels of government. They also support business planning by project developers, and product line planning by technology developers.

F. *Wave resource classification system (beta-version)*

The wave resource classification system is based on the available wave power, J (W/m), as a measure of project opportunity,

$$J = \rho g \sum_i S_i C_{g,i} \Delta f_i$$

where ρ is the sea water density, $C_{g,i}$ is the group velocity at frequency f_i, and $S_i \Delta f_i$ is the total variance at frequency f_i [8].

As shown in Table II, this classification system delineates four power classes in descending order of energy resource, I ($22.8<J$), II ($5.7<J\leq 22.8$), III ($1.1<J\leq 5.7$), and IV ($J\leq 1.1$), where wave power, J, is in units of kW/m. The peak period, T_P (s), bandwidth containing the most wave energy is introduced to identify the dominant wave energy transfer mechanism at a site among those delineated for US wave climates, local wind seas ($0<T_P\leq 7$), short-period swell ($7< T_P \leq 10$) and long-period swell ($10<T_P$). This information is important for WEC design, allowing an assessment of the dominant resonant bandwidth that a WEC must operate within to optimize power capture. The dominant peak period band could be

interpreted as a project constraint metric or a measure of the quality of the wave energy resource. Details of this resource classification system are given in [12].

TABLE II
WAVE ENERGY RESOURCE CLASSIFICATION [12]

POWER CLASS		I 22.8<J	II 5.7<J≤22.8	III 1.1<J≤5.7	IV J≤1.1
1	0<T_P<7	I(1)	II(1)	III(1)	IV(1)
2	7≤T_P≤10	I(2)	II(2)	III(2)	IV(2)
3	10<T_P	I(3)	II(3)	III(3)	IV(3)

Classification parameters were computed using modelled spectral partitioned wave parameters output from the phase II WaveWatch III® (WWIII) 30-year hindcast [13]. This provided full coverage of the entire US coastline at a resolution of 4 arc-minutes but was limited to sites with intermediate and deep depths with normalized peak frequencies of $f_P > 0.05\sqrt{g/h}$.

The delineation of power classes I-IV is adjusted to discern the distinct geo-spatial regional resource trends for US coastal waters shown in Figure 2. The threshold value separating classes II and III corresponds approximately to the *median* wave power computed for the US (J=5.7 kW/m). The threshold between I and II (J =22.8 kW/m) is set one standard deviation higher than the mean value (J =12.0 kW/m), and that between III and IV (J =1.1 kW/m) one standard deviation lower than the mean value.

A map showing the distribution of wave resource (power) classes based on total power is shown in Figure 2 and reveals distinct regional trends. An alternative classification system shown in Figure 3, allows a higher fidelity assessment that accounts only for the power transferred in the dominant wave period band. Like wind, these resource classification maps provide useful information for regional energy planners evaluating the contribution of wave energy in their renewable energy portfolios for their state or region; or wave energy developers assessing market potential. They will be upgraded to include shallow ($f_P < 0.05\sqrt{g/h}$) nearshore areas at feasibility to design-level resolutions between 200-300 m using high-resolution regional 32-year Simulating WAves Nearshore (SWAN) model hindcasts planned for the entire US coastline, e.g., [14].

G. Tidal resource classification system (conceptual)

The tidal resource classification system, likewise, uses the available annual mean power density, P (kW/m^2), as a measure of project opportunity,

$$P = \frac{1}{2}\frac{1}{N}\rho\sum_{j=1}^{N} U_j^3$$

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. A second constraint parameter, e.g., cross-sectional area, A, may be required to account for theoretical limits on this power density as described in [15], but the physical resource attribute that would serve as the best proxy for assessing these limits needs to be determined. Alternatively, it may be determined that adopting turbulence intensity as parameter to characterize project risk, like the conditions classification system described below, may be preferred.

A strawman tidal resource classification system table is shown in Table III. Three power classes are delineated starting with Class III (0.5-1 kW/m^2), which is considered a minimum resource for a utility scale project with a minimal power density of 0.5 kW/m^2 corresponding to a tidal current of approximately 1 m/s. A Class II resource has power densities between 1 and 2 kW/m^2, and a Class III, power densities above 2 kW/m^2.

TABLE III
STRAWMAN TIDAL ENERGY RESOURCE CLASSIFICATION

POWER CLASS		I 2<P	II 1≤P≤2	III 0.5<P<1
1	A>TBD	I(1)	II(1)	III(1)
2	TBD ≤ A ≤TBD	I(2)	II(2)	III(2)
3	A <TBD	I(3)	II(3)	III(3)

Classification parameters can be computed from Regional Ocean Modelling System (ROMS) hindcasts conducted for regional assessments of the US tidal energy resource at a 0.003-degree grid resolution [16]. Efforts are also underway to refine modelling in some regions to provide more accurate hindcast outputs.

H. Wave conditions classification system (conceptual)

The wave conditions classification system concept, like the wind conditions classification system in IEC TS 61400-1, is designed to classify wave conditions for normal stochastic sea states (NSS) and extreme stochastic sea states (ESS) with 50-year return periods [7].

The main parameter selected for this classification system is the significant wave height with a 50-year return period, H_{m50}, the main parameter characterizing design wave loads for ESS in the IEC design standard. Like U_{ref} the wind conditions classification, H_{m50} is a key metric for calculating the wave load for the ESS. H_{m50} has also been shown to be well correlated with the mean significant wave height within each regional wave climate [17]. It, therefore, can serve as the reference parameter, H_{ref}, to derive wave load conditions for NSS conditions.

Introducing peak period, T_P, as the second classification parameter, while defining a more complete ESS characterization, does not align with standard methods for selecting the "worst case" value for the DLC by trial and error, e.g., [7], because this value is not known *a priori*. In addition, the T_P used for a DLC is both WEC dependent and subsystem dependent. Nevertheless, consideration will be given to introduce upper bound peak periods for building NSS DLCs based on the dominant peak period bands identified for transferring wave energy in the wave energy resource classification system.

A strawman wave conditions classification system with three WEC classes (I, II, and III) is shown in Table IV. Class delineation, including upper bounds on H_{ref} and class bandwidths of 5 m are initial estimates based on the distribution of H_{m50} values along the US coastline as depicted in Fig. 5 [18]. These initial estimates were computed from 30-year WWIII hindcasts [19], but will be upgraded with more accurate high-resolution SWAN hindcasts that include shallow near-shore [20] and corrected for model bias [21].

TABLE IV
STRAWMAN WEC (CONDITIONS) CLASSIFICATION

Class		I	II	III	S
H_{ref} (m)		15	10	5	Specified by designer
1	$0<T_P<7$	I(1)	II(1)	III(1)	
2	$7\leq T_P\leq 10$	I(2)	II(2)	III(2)	
3	$10<T_P$	I(3)	II(3)	III(3)	

This classification delineates three WEC classes like the wind conditions classification system. A WEC designed for an offshore site with an estimated H_{m50} between 10 m and 15 m, e.g., 12 m, would use an ESS DLC based on H_{m50} value of 15 m.

I. *Tidal conditions classification system (conceptual)*

The tidal conditions classification system concept, is designed to classify tidal conditions for the normal current model (*NCM*), currents between cut-in and cut-out, and the extreme current model (*ECM*) based on the current coinciding with the peak spring tide as defined in the design standard for marine energy systems IEC TS 62600-2 (ED2).

A strawman tidal conditions classification system closely modelled after the IEC wind turbine classification system with three TEC classes (I, II, and III) and three subclasses (A, B, C), is shown in Table V. This strawman classification and delineation is also similar to one proposed in [23]. Class delineation, including upper bounds on U_{ref} and class bandwidths of 1 m/s, and upper bounds on I_{ref} and class bandwidths of 0.10, are initial estimates based on field data collected at US tidal sites [23], [24] and expert judgment.

TABLE V
STRAWMAN TIDAL CONDITIONS (TEC) CLASSIFICATION

TEC Class		I	II	III	S
U_{ref} (m/s)		3.5	2.5	1.5	Specified by engineer
A	I_{ref} (-) @1.5 m/s	0.20			
B		0.15			
C		0.10			

This classification delineates nine TEC classes like the wind conditions classification system. Example classifications for three US sites are given in Table VI. A TEC designed for Verdant Power's Roosevelt Island Tidal Energy (RITE) Project site, with a U_{ref} =2.4 m/s and I_{ref} =0.18 [23], would be designated a Class IIA TEC, and would apply an ECM DLC based on U_{ref} =2.5 m/s and I_{ref} =0.20.

TABLE VI
TIDAL CONDITIONS AT US PROJECT SITES

Project	Reference	Site measurement		Design condition		TEC Class
		U_{ref} (m/s)	I_{ref}	U_{ref} (m/s)	I_{ref}	
RITE	Gunawan et l. 2014	2.4	0.18	2.5	0.20	IIA
Admiralty Inlet	Thomson et al. 2012	2.0	0.09	2.5	0.10	IIC
Nodule Point	Thomson et al. 2012	2.6	0.10	3.0	0.10	IC

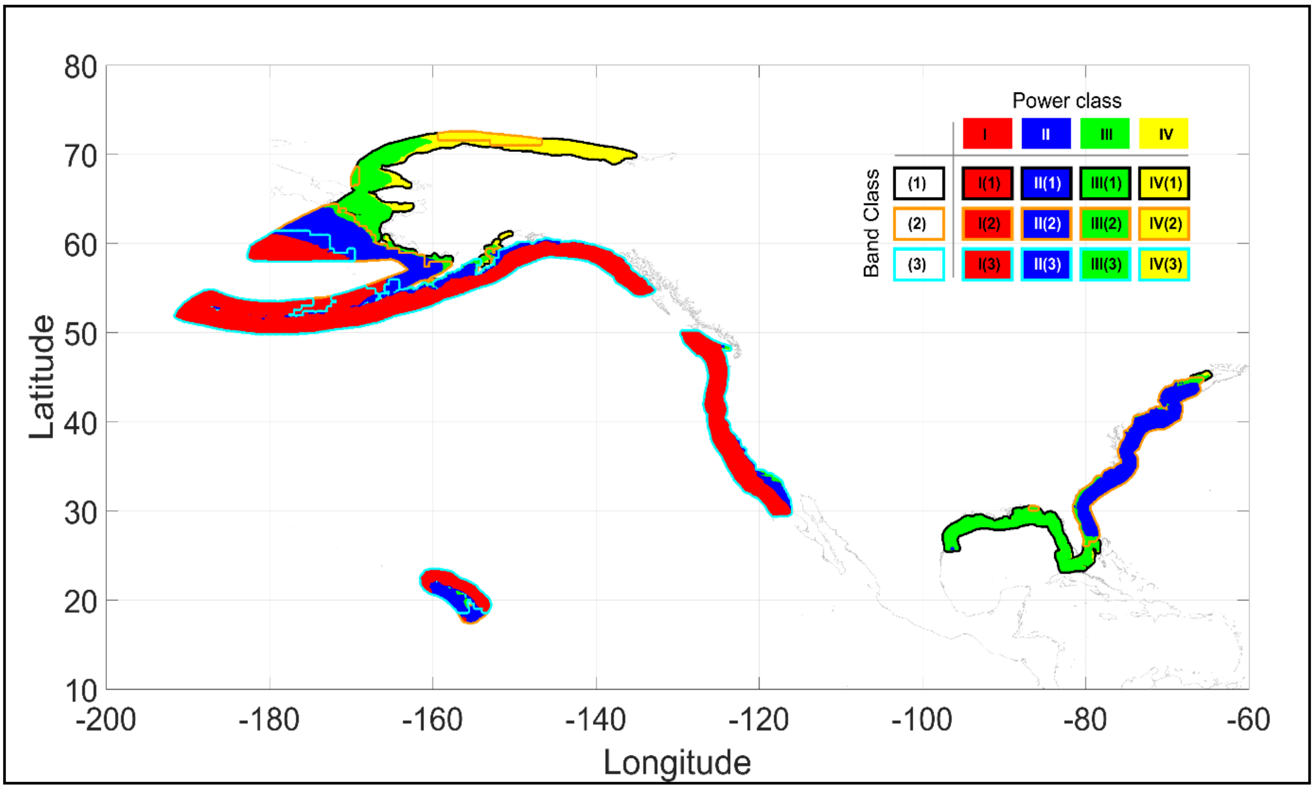

Fig. 2. Wave energy resource classification system, total power [Ahn et al. 2019]

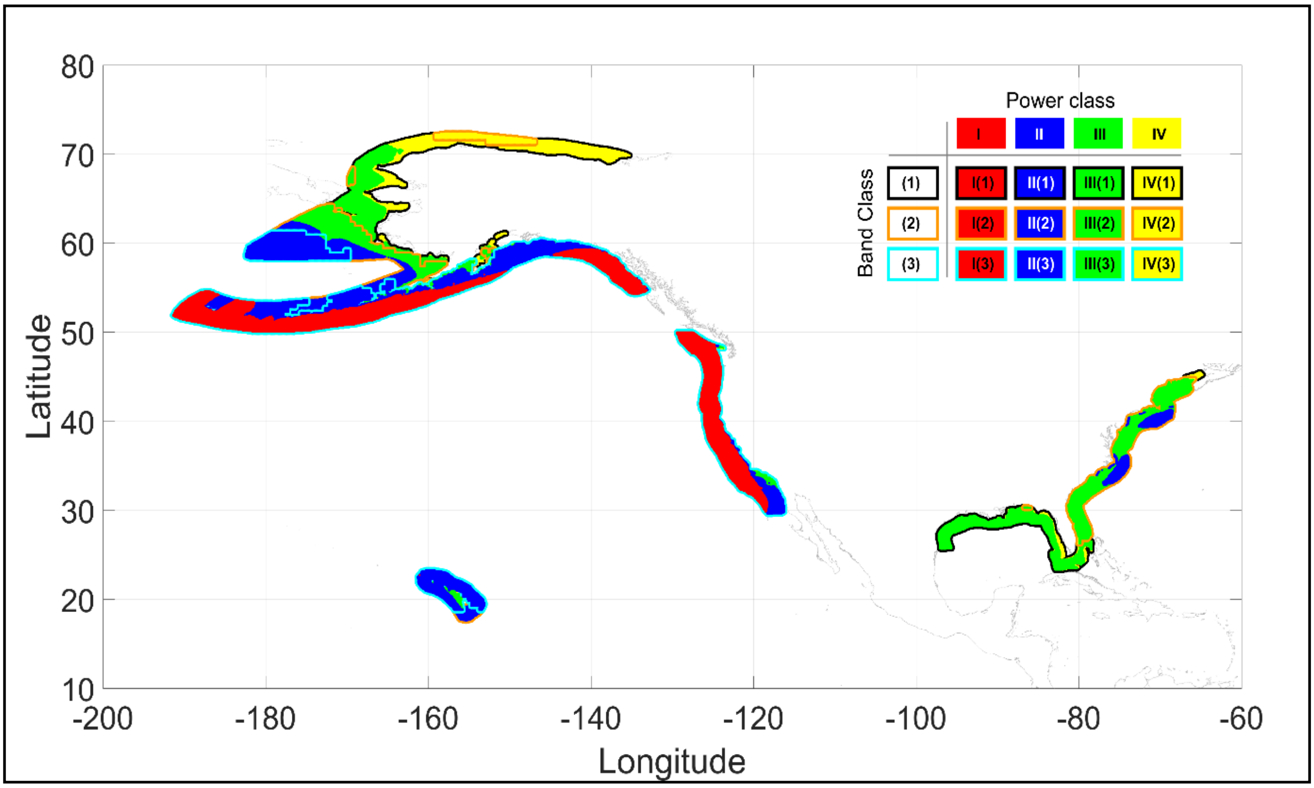

Fig. 3. Wave energy resource classification system, maximum band power [Ahn et al. 2019]

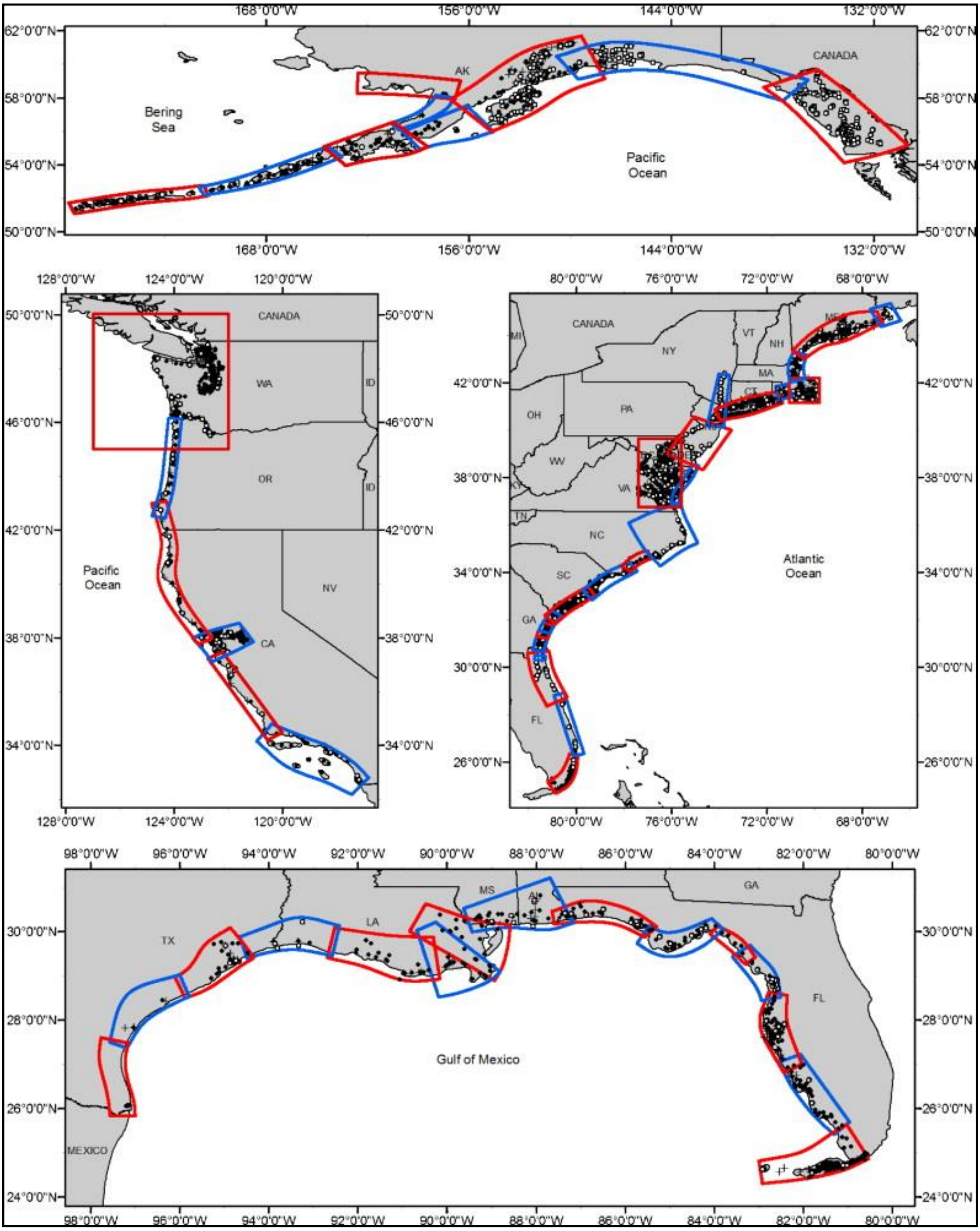

Fig. 4. Map of computational grids and calibration data source for US tidal energy resource assessment [16].

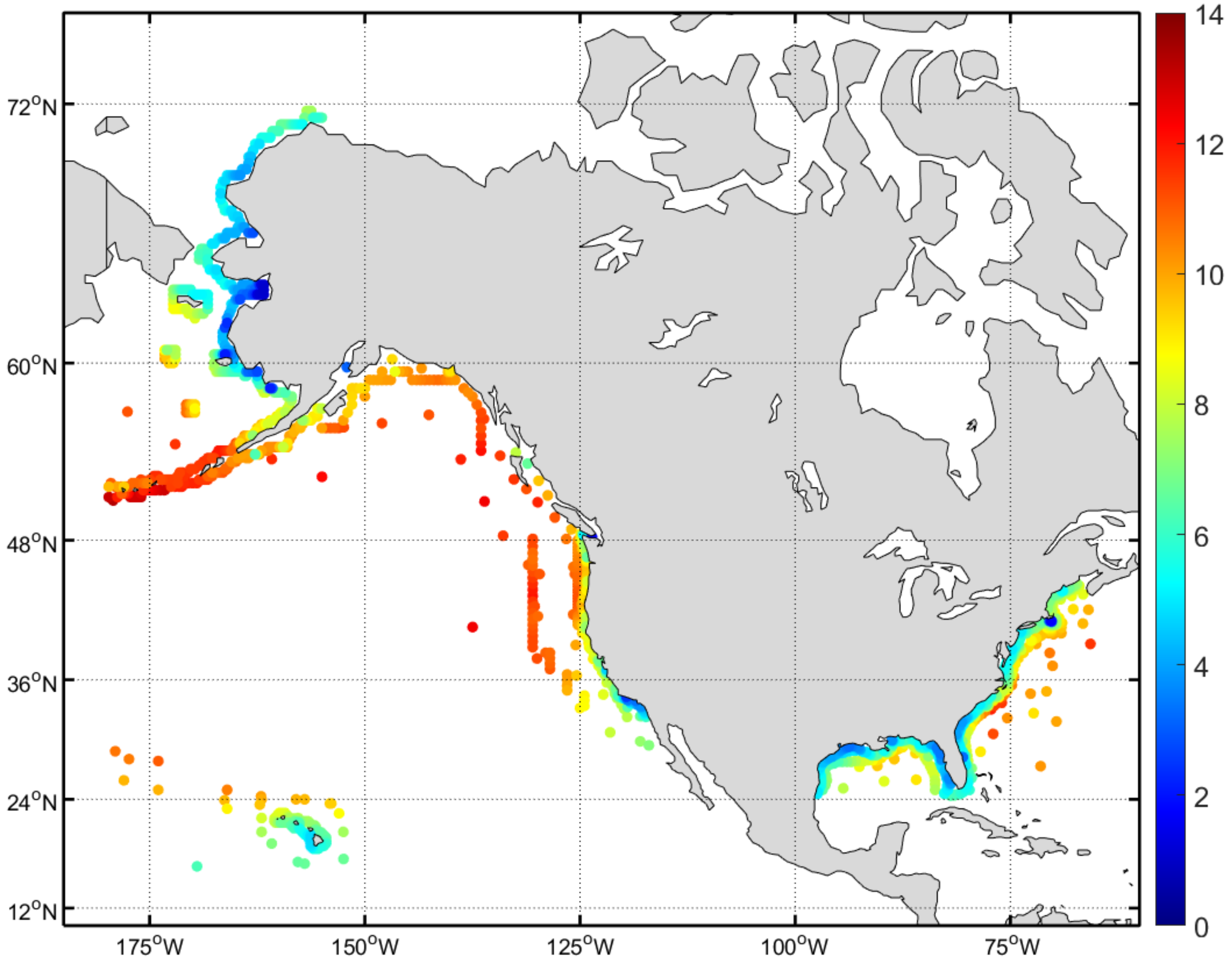

Fig. 5. Geographical distribution of H_{m50} for US coastline [18].

IV. CONCLUSIONS

Marine energy classification systems, like those developed for wind, can provide significant benefits to the industry by facilitating resource assessment for energy planning and project development, through resource (project) classification; and device design, certification, product-line development and manufacturing through conditions (device) classification.

Four US marine energy classification systems are described herein, including a beta-version wave resource classification system, and conceptual tidal resource, wave conditions, and tidal conditions classification systems. Design requirements for these classification systems are highlighted as well as the data sources and steps for building them.

Energy resource classification systems rely primarily on power density as the main metric gaging project opportunity, but resource classification can be improved by introducing other parameters that qualify or constrain the total available resource. For conditions classification, the main classification parameter should serve as the basis to model the ESS DLC, but correlations with parameters representing mean annual conditions to model NSS DLCs are needed.

The benefits of these classification systems can only be fully realized through their codification within international standards and certification. Therefore, knowledge of the pertinent IEC standards is critical to ensure these classification systems are aligned accordingly, and to identify the standards that can be fully complemented by classification.

The quality of resource and conditions classification tools (accuracy fidelity, resolution, spatial coverage) depends on the data sources used to compute the classification parameters. Validated high-resolution model hindcasts, particularly for resource classification that assess mean power density, can provide full spatial coverage at resolutions sufficient to conduct feasibility- to design-level resource assessments. However, measurements are also essential data sources when model hindcasts fail to provide the level of fidelity or accuracy to resolve parameters on extreme conditions or turbulence statistics.

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