2022 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
WATER POWER TECHNOLOGIES OFFICE

WBS 2.1.5.401 – Model Validation and Site Characterization for Early Deployment MHK Sites and Establishment of Wave Classification Scheme

Photo from Christopher Pike

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Project Overview

Project Summary

The "Resource Characterization" project delivers the data and tools needed to engineer robust marine renewable energy (MRE) devices and projects. The project measures resource details at commercially promising sites, runs high resolution models of promising sites and regions, and develops classification schemes that streamline device engineering, project development, and increase investor confidence.

Intended Outcomes

1. High resolution wave energy resource and wave condition metrics based on 42-year hindcasts that span the entire U.S. exclusive economic zone (EEZ)
2. Resource measurements at commercially promising sites
3. Wave and tidal resource classification schemes

Impact: Publicly available data will inform technology and project designs, and support more accurate assessments of MRE opportunities and risks at reduced costs.

Project Information

Project Information
Principal Investigator(s)
• Levi Kilcher (NREL) • Zhaoqing Yang (PNNL) • Vince Neary (Sandia)
Project Partners/Subs
Oregon State University, Georgia Tech., TerraSond, Coastal Data Information Program, Caribbean Coastal Ocean Observing System, University of Hawaii, North Carolina State University, Ocean Renewable Power Company
Project Status
Ongoing
Project Duration
2016 - 2022
Total Costed (FY19–FY21)
$8,387K

Alignment with the Marine Energy Program

Foundational and Crosscutting R&D

Resource assessment, characterization, & extreme conditions data:

- Aids the engineering, design, optimization of MRE devices and arrays.
- Data is publicly disseminated via electronic data-portals and through publications.

Measurements and model outputs:

- Detailed resource and conditions statistics (e.g., turbulence and extreme wave heights).
- Important inputs to MRE devices simulation tools.

Data Sharing and Analysis

Open access data for maximum availability:

- Marine Energy Atlas & other tools
- Helps stakeholders identify new project and technology opportunities.

Maintaining engagement with international experts:

- Participation in international conferences.
- Active involvement in International Electrotechnical Commission technical committee on Marine Energy (IEC TC114).

Technology-Specific Design and Validation

Site-specific resource characterization data helps to:

- quantify project economics (cost)
- identify grid-integration opportunities and challenges
- conduct safe and efficient installation, operations and decommissioning (e.g., weather windows)
- predict maintenance cycles.

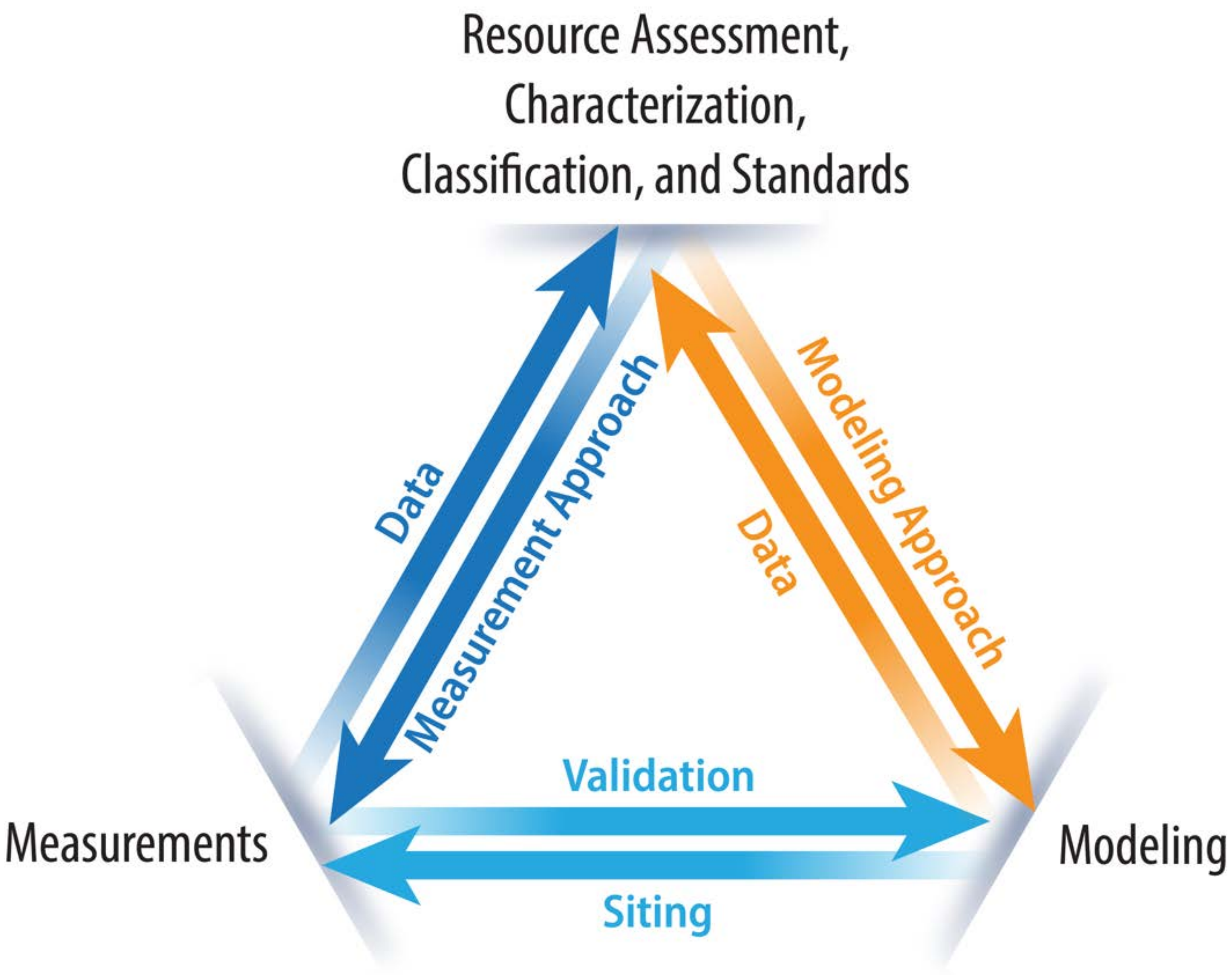
Classification systems to define the energy resource and device classes:

- Evaluated within the standards and certification processes.
- Standardization improves investor/financier confidence in technologies and projects.

Project Management

- Research areas divided between labs:
  - Measurements led by NREL
  - Modeling led by PNNL
  - Classification led by Sandia
- Lab collaboration: delivers consistent results, leverages expertise, and pools resources
- Project advisory committee: informs project trajectory
- Measurement sites and model domains: selected based on ‘early market’ assessments, industry input, and DOE priorities
- Industry collaboration: subcontracts to local organizations
- Data dissemination via Marine Energy Atlas and Portal and Repository for Information on Marine Renewable Energy (PRIMRE)

Project Objectives: Technical Approaches



Resource assessment and characterization:

- Measurement and modeling data are synthesized, analyzed, and validated
- Outputs: key statistical datasets and other high-level analysis that are important inputs to device design and project siting

Measurements: State-of-the-art approaches following industry standards

- StableMoor buoys capture velocity and turbulence at device hub-height
- Waverider buoys are de-facto ‘standard’ for resolving wave directional spectrum

Siting informed by stakeholder engagement, data gaps, and model results

Models: high-resolution unstructured grid

- Efficient performance and high accuracy
- High temporal resolutions
- Fine special resolutions (even in the near shore – not the case with structured grids)

These outputs provide the marine energy community with the resource data needed to develop marine energy technologies and projects.

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

- Resource Measurements
- High-resolution Resource Models
- Key statistical datasets
- Classification systems
- Marine Energy Atlas

Outcomes:

Resource data (measurements and models)

- Technology developers have the support they need to design devices that match the resource
- Project developers are able to identify the most promising sites

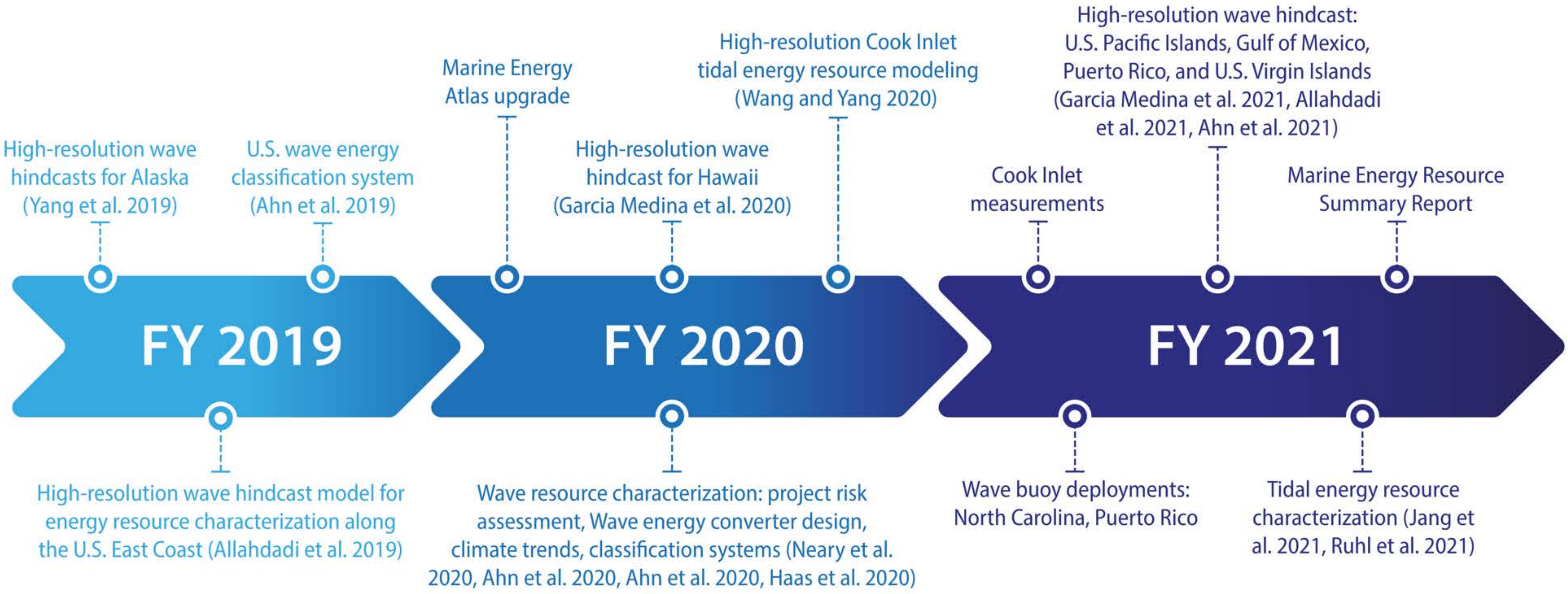
Classification systems (like those for wind industry)

- Resource assessment is streamlined and codified
- Designs and devices are certified
- Product-line development is enabled for wave and current energy devices

The Marine Energy Atlas

- Diverse stakeholders can visualize and access the resource data they need

Project Timeline



Project Budget

	FY19	FY20	FY21	Total Actual Costs FY19–FY21
	Costed	**Costed**	**Costed**	**Total Costed**
NREL	$565K	$992K	$1,512K	$3,069K
PNNL	$797K	$1,014K	$896K	$3,218K
Sandia	$656K	$658K	$715K	$2,029K
TOTAL	**$2,018K**	**$2,664K**	**$3,123K**	**$8,316K**

End-User Engagement and Dissemination

Novel Data Dissemination

Outputs from measurements and models are made publicly available

- Data are analyzed before dissemination – providing validated and quality-controlled statistical datasets
- Open access democratizes important inputs for device design and project siting for all stakeholders

Marine Energy Atlas

- open access tool for data visualization and download

Public Measurement Datasets

- MHK Data Repository
- Coastal Data Information Program (CDIP)

Academic and Industry Engagement

Publications

- 11 in prep; 25 from 2020-2022
- See final slides for full list

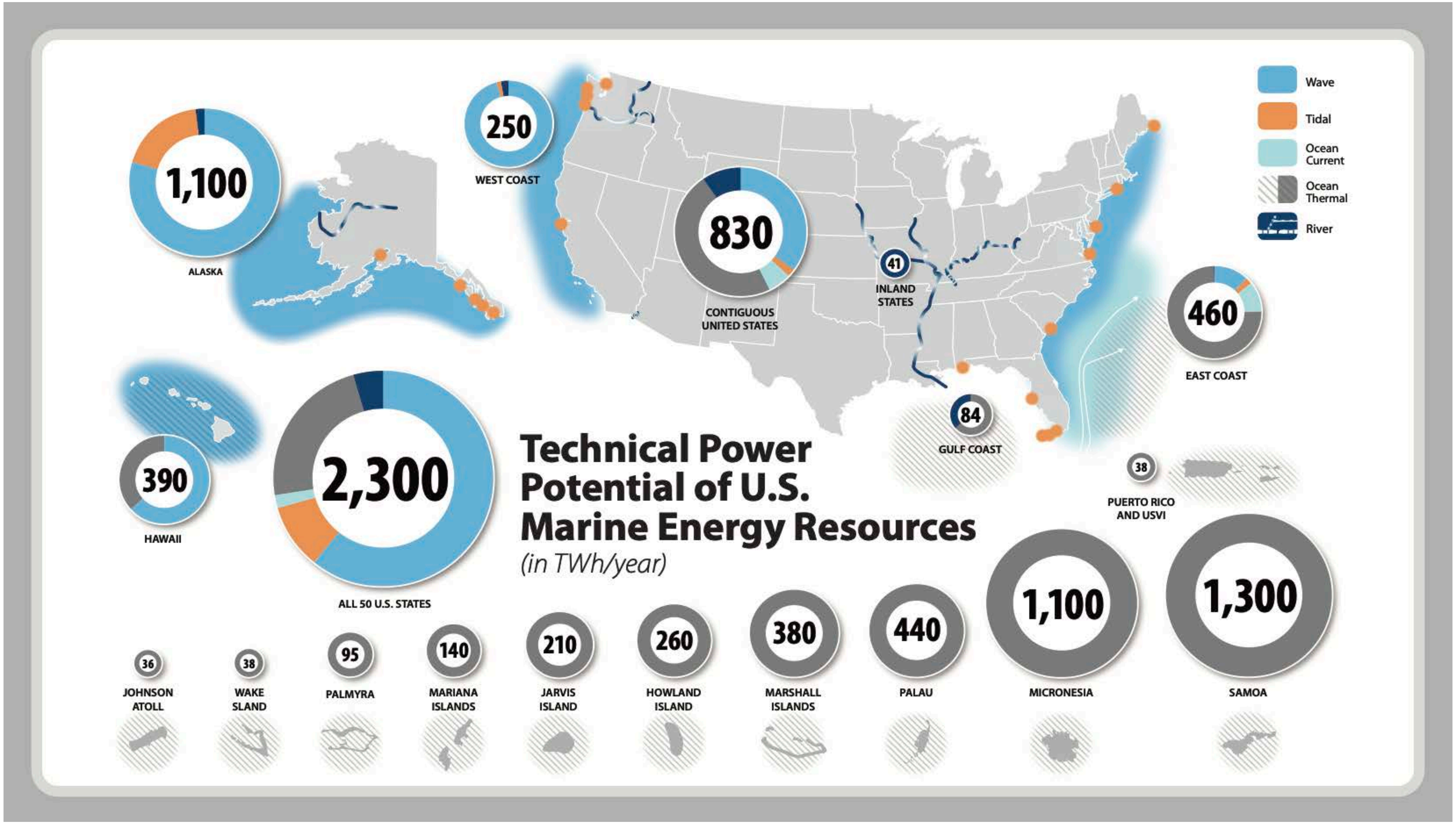
Conferences

- Alaska Sustainable Energy Conference (May 2022)
- Ocean Sciences Conferences (2020, 2022)
- Clean Currents (October 2021)
- American Geophysics Union Fall Meetings (2016-2021)

Marine Energy Atlas

MHK
Marine and Hydrokinetic Data Repository
U.S. DEPARTMENT OF ENERGY

MRE Resource Summary Report



Kilcher, Fogarty, and Lawson. 2021. ***Marine Energy in the United States: An Overview of Opportunities***. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-78773. https://www.nrel.gov/docs/fy21osti/78773.pdf

Marine Energy Atlas

- Online, open-access hub to visualize, analyze, and download spatial datasets
- User-friendly portal for accessing High-Resolution WPTO Wave Hindcast Dataset
  - Time-series of IEC standard wave parameters in US Coastal waters.
  - 200m spatial resolution (in shallow water), covers EEZ
  - 32 years (1979-2021), expanding to 42 soon (2011-2020)

High-Res Wave Data also available

- AWS public datasets – cloud computing access
- MHKiT – local workstation data access

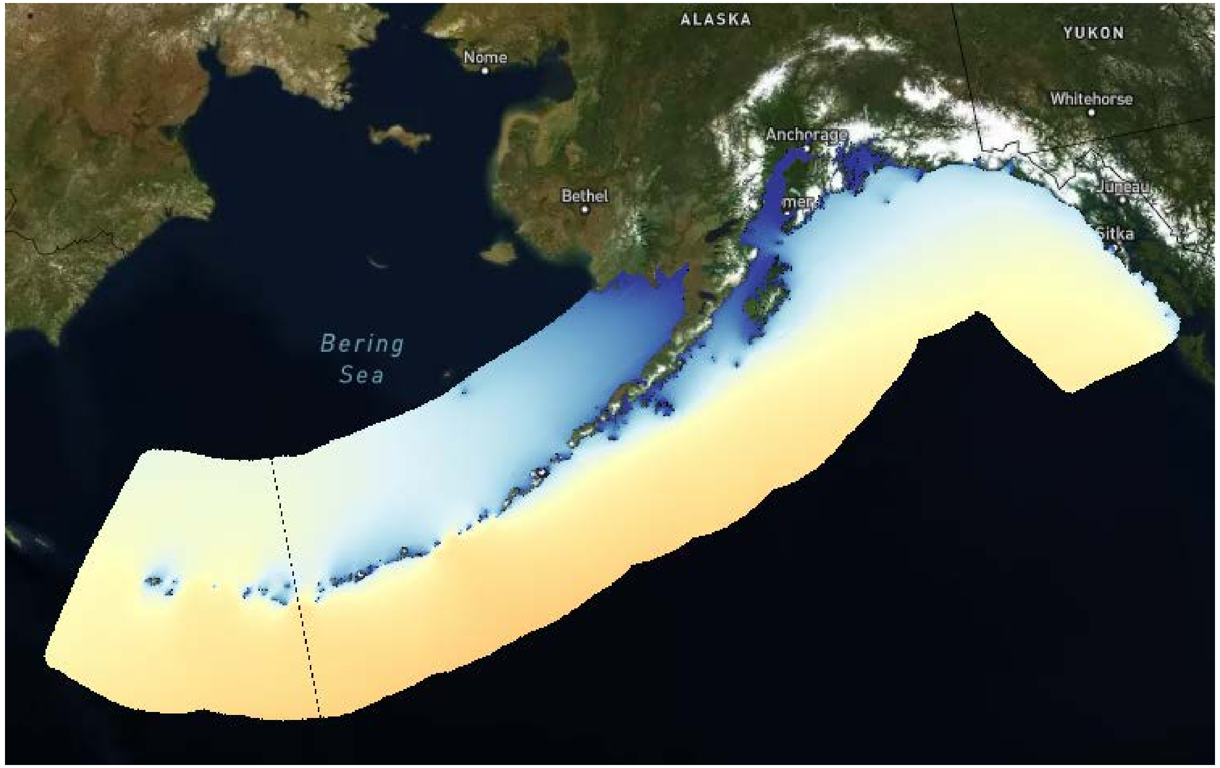
New feature: **Capacity Factor Tool**

Users can calculate WEC Capacity Factors across the entire WPTO Hindcast Dataset (image at right)

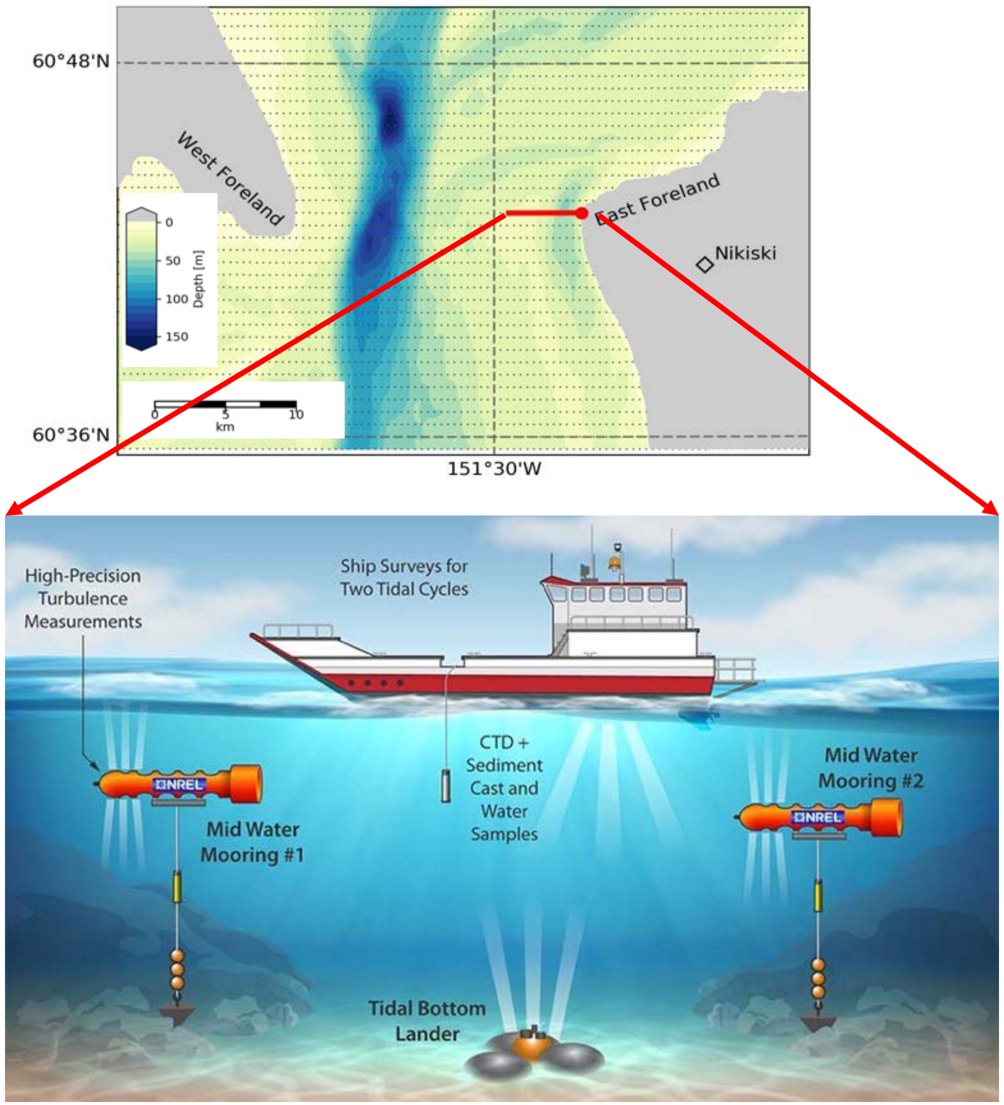
Future Work:

- Add more discoverability and visual configurations to increase impact of the Atlas
- Upcoming tidal model datasets: similar accessibility and visualizations as the wave datasets

Capacity Factor Tool output

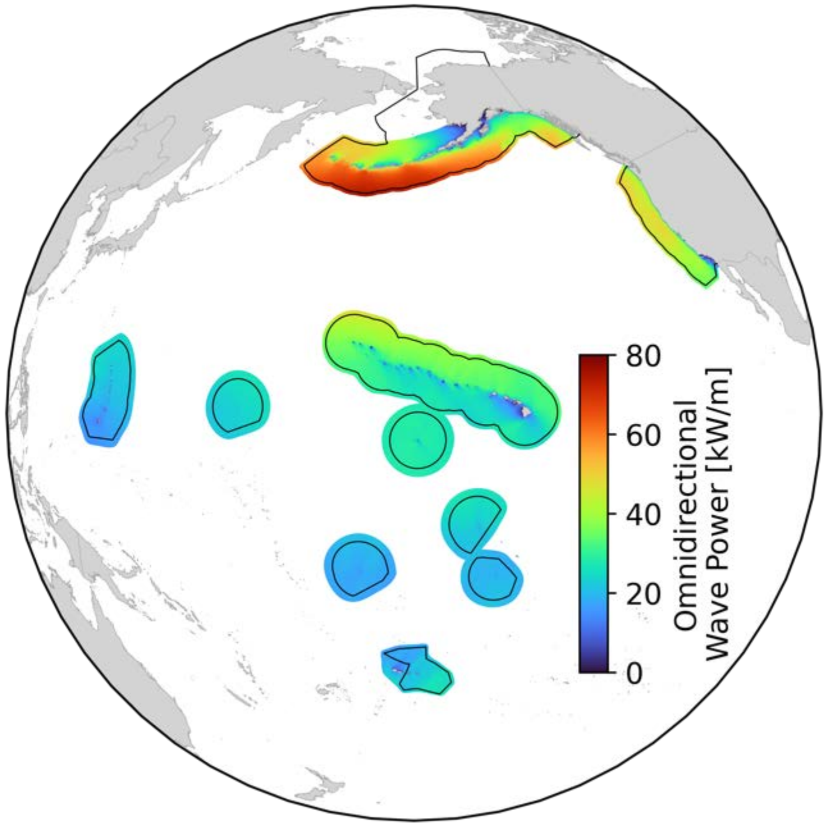


Cook Inlet — Tidal Resource Characterization Measurements

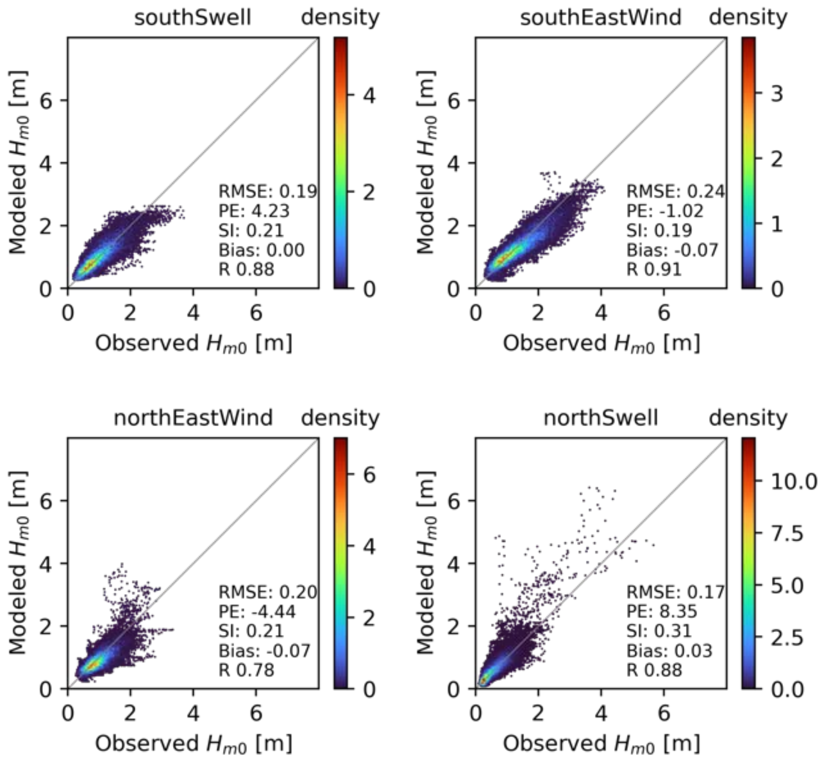


High-Resolution Wave Hindcasts for the U.S. Pacific EEZs

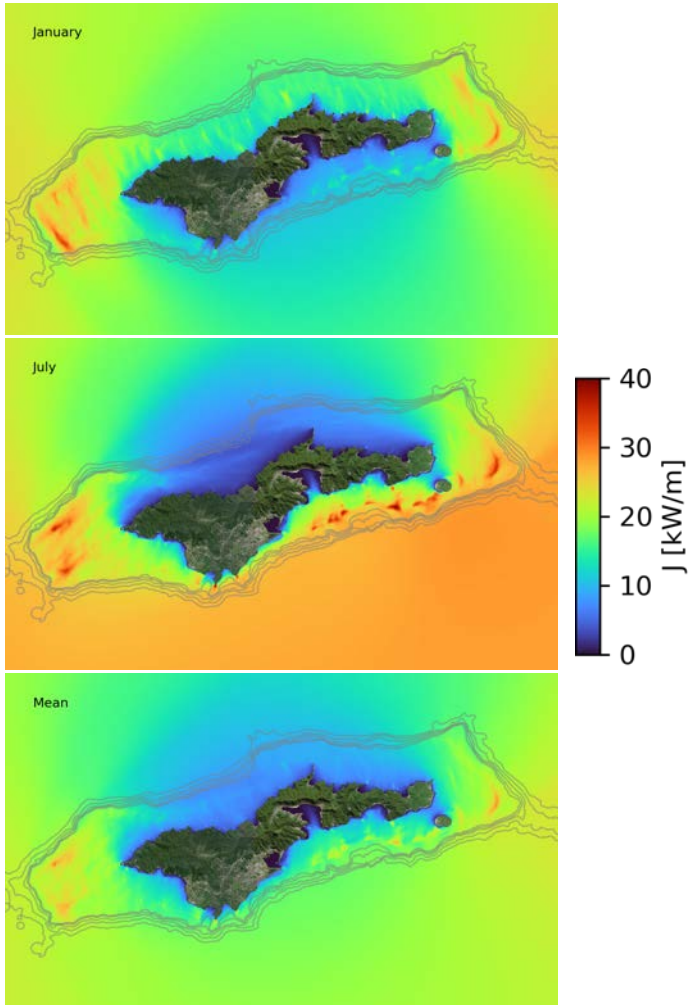
- Developed and validated high-resolution wave hindcast models for the US EEZs in the Pacific Ocean



Simulated mean Omnidirectional wave power in the US EEZs in the Pacific Ocean



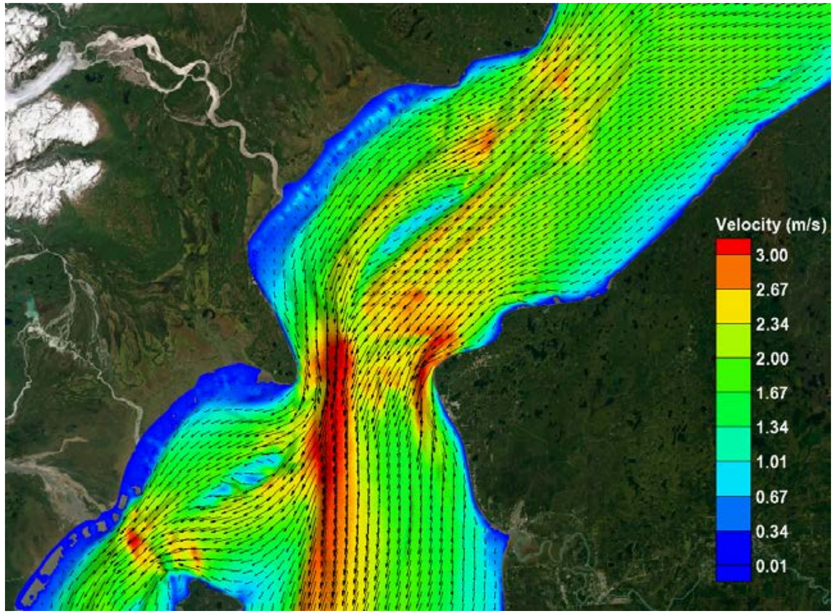
Model validation around American Samoa showing the main wave climate components



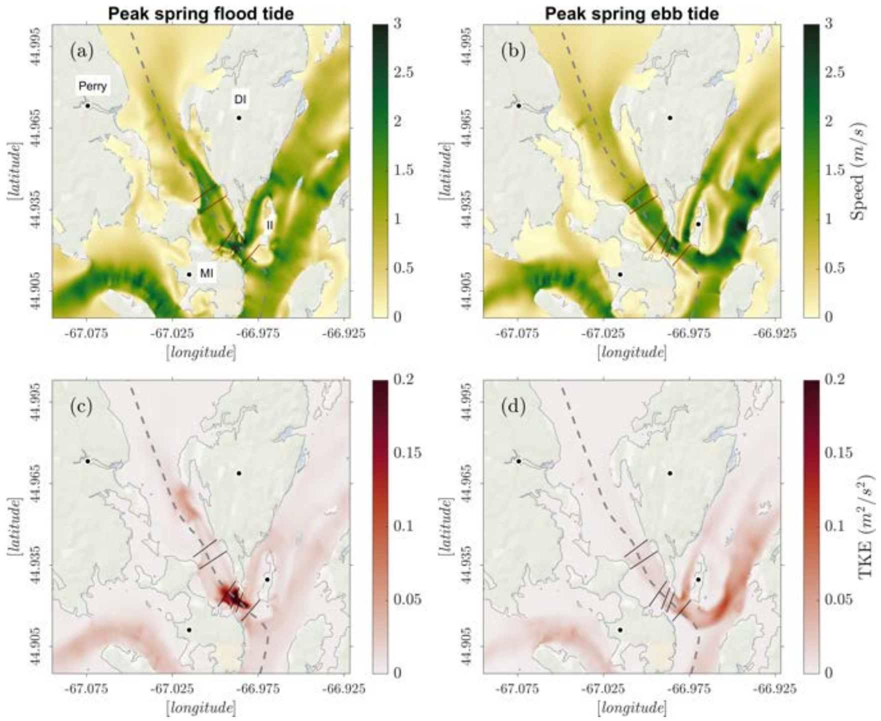
Seasonal wave power around Tutuila, American Samoa

Tidal Energy Resource Characterization Modeling

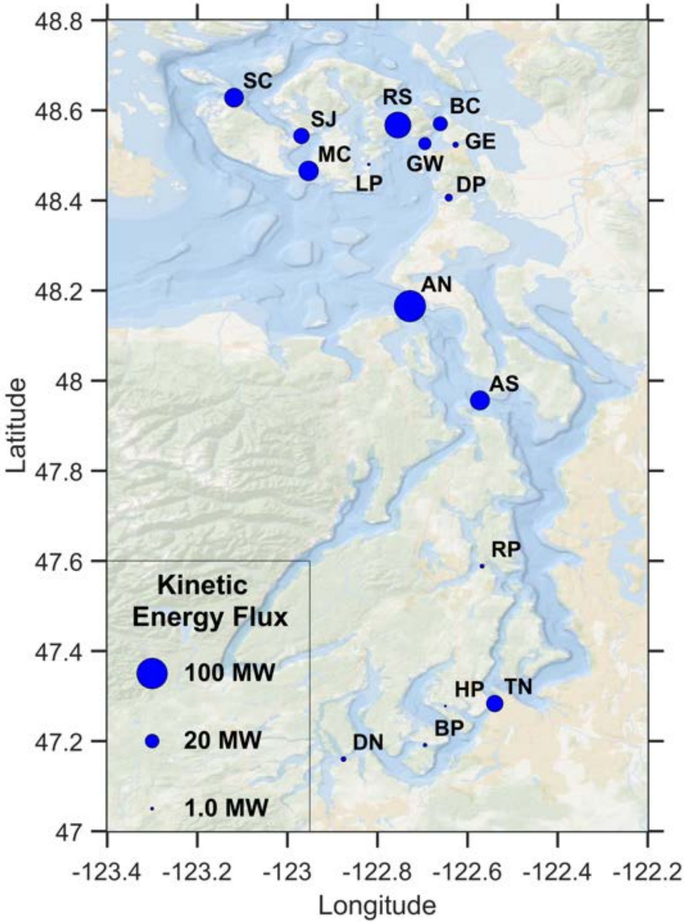
- Developed and validated high-resolution tidal hydrodynamic models for top tidal energy sites



Simulated depth-averaged current in Cook Inlet, AK



Simulated tidal currents and turbulent properties in Western Passage, Maine

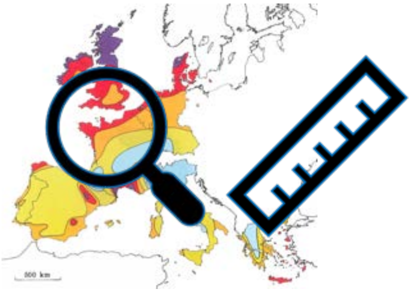


Kinetic energy fluxes at tidal energy hot-spots in Puget Sound

Resource & Device Classification Systems (Neary et al. 2019, 2020)

Classification (taxonomy) is an organizational tool that reduces many things (e.g., resources, devices) down to a few classes with similar key attributes to streamline their evaluation and treatment.

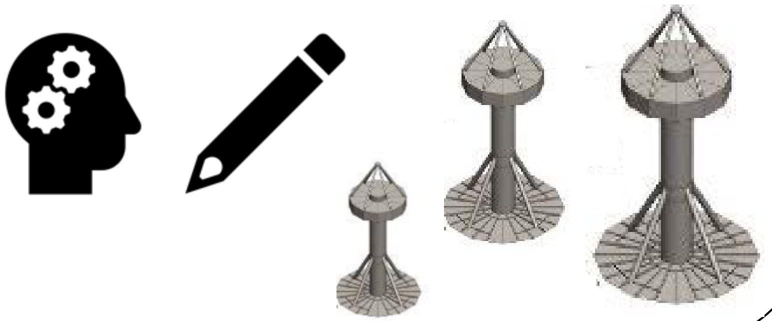
Marine energy classification systems, like those for wind industry, streamline and codify resource assessment, design and device-type certification for wave and current energy devices



Resource Classification –streamline and codify assessment for energy planning and project development

Device Classification –

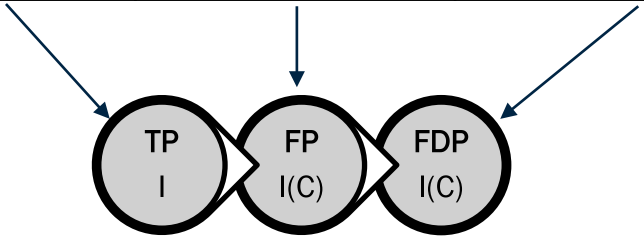
streamline and codify device design, device-type certification, product-line development and manufacturing



Neary, Haas and Colby "Marine Energy Classification Systems: Tools for resource assessment and design," presented at the *European Wave and Tidal Energy Conference*, 2019.
Neary, Haas and Colby "Marine Energy Classification Systems: Tools for resource assessment and design," white paper submitted to IEC/TC 114, June 2020.

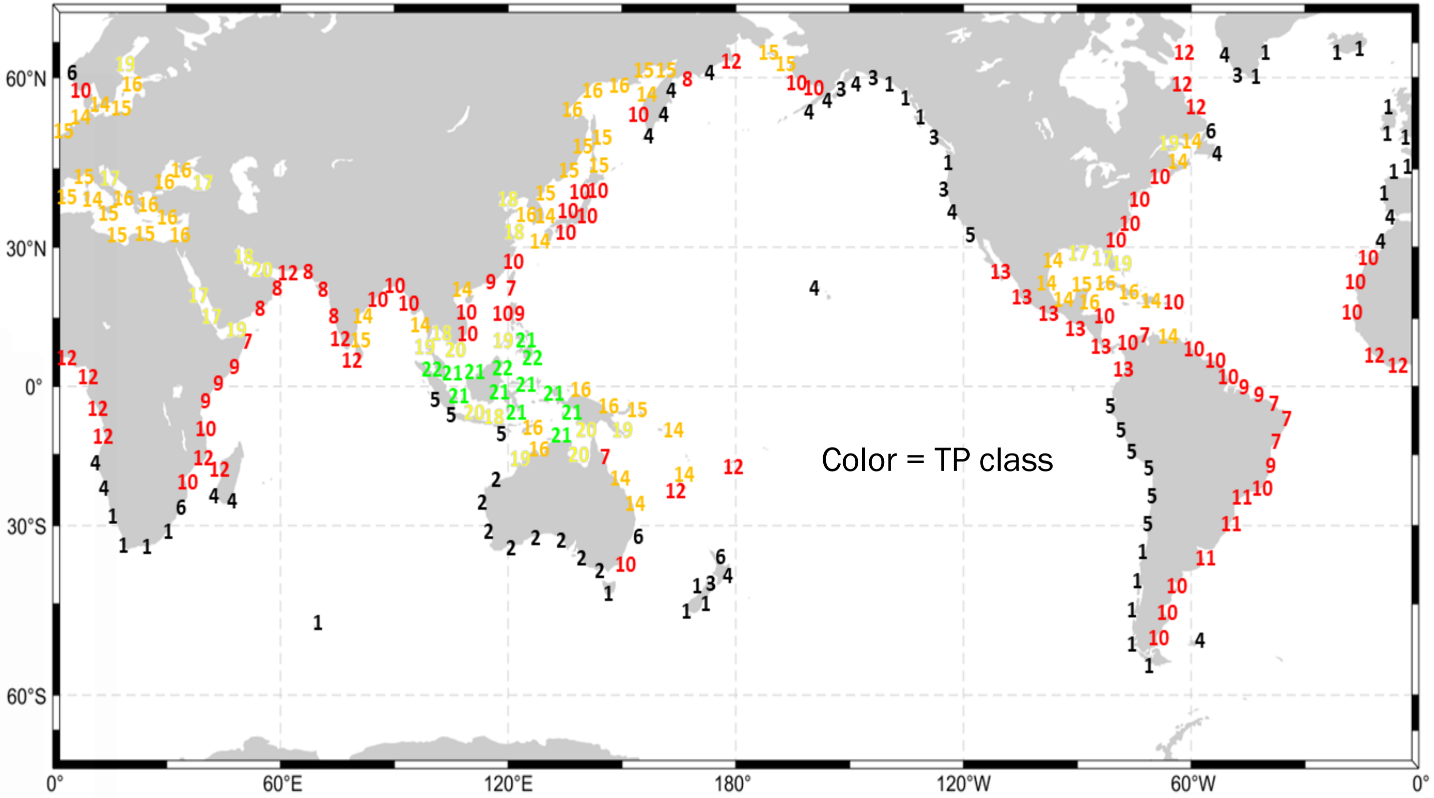
Global wave energy resource classification system (Ahn et al. 2022)

Power Class (I-V)	Total Power (TP)	Max Freq-Constr. Power (FP)	Max Freq-Dir Constr. Power (FDP)
Sub-Class (A-D)	N/A	Period band w/ Max FP	Period band with Max FDP



Index	Resource class (TP)		Resource class (FP)		Resource class (FDP)
1.	I	-	I (C)	-	I (C)
2.	I	-	I (D)	-	I (D)
3.	I	-	I (C)	-	II (C)
4.	I	-	II (C)	-	II (C)
5.	I	-	II (D)	-	II (D)
6.	I	-	II (C)	-	III (C)
7.	II	-	II (B)	-	II (B)
8.	II	-	II (C)	-	II (C)
9.	II	-	II (B)	-	III (B)
10.	II	-	III (B)	-	III (B)
11.	II	-	III (B)	-	III (C)
12.	II	-	III (C)	-	III (C)
13.	II	-	III (D)	-	III (D)
14.	III	-	III (B)	-	III (B)
15.	III	-	III (B)	-	IV (B)
16.	III	-	IV (B)	-	IV (B)
17.	IV	-	IV (B)	-	IV (B)
18.	IV	-	IV (A)	-	V (A)
19.	IV	-	IV (B)	-	V (B)
20.	IV	-	V (A)	-	V (A)
21.	V	-	V (A)	-	V (A)
22.	V	-	V (B)	-	V (B)

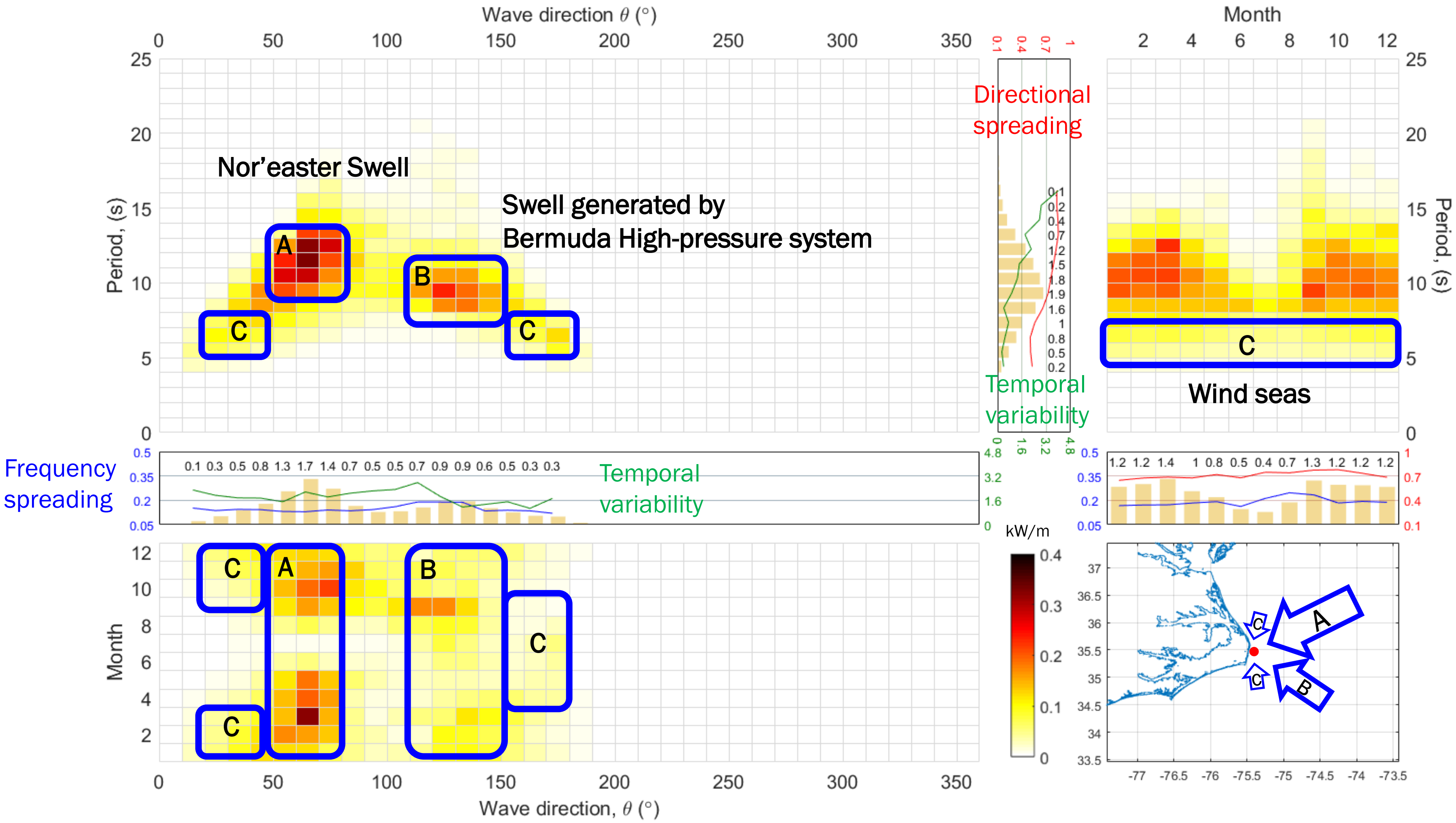
Power class (kW/m)		I 16<J	II 7.3<J≤ 16	III 2.5<J≤7.3	IV 0.8<J≤2.5	V J≤0.8
A	$0 < T_P(s) < 6$	IA	IIA	IIIA	IVA	VA
B	$6 \leq T_P(s) \leq 10$	IB	IIB	IIIB	IVB	VB
C	$10 \leq T_P(s) \leq 14$	IC	IIC	IIIC	IVC	VC
D	$14 < T_P(s)$	ID	IID	IIID	IVD	VD



Ahn, S., V.S. Neary, and K.A. Haas, Global wave energy resource classification system for regional energy planning and project development. Renewable and Sustainable Energy Reviews, 2022. 162: p. 112438. https://doi.org/10.1016/j.rser.2022.112438.

Methods for wave energy resource characterization (Ahn et al. 2020)

Joint & marginal distributions to identify & characterize wave-energy systems



Two dominant wave systems

Energy	A>B
Temporal variability	A>B
Frequency spreading	A>B

WEC design

Design	A	B
Resonant	12 s	9 s
Direction	70°	130°

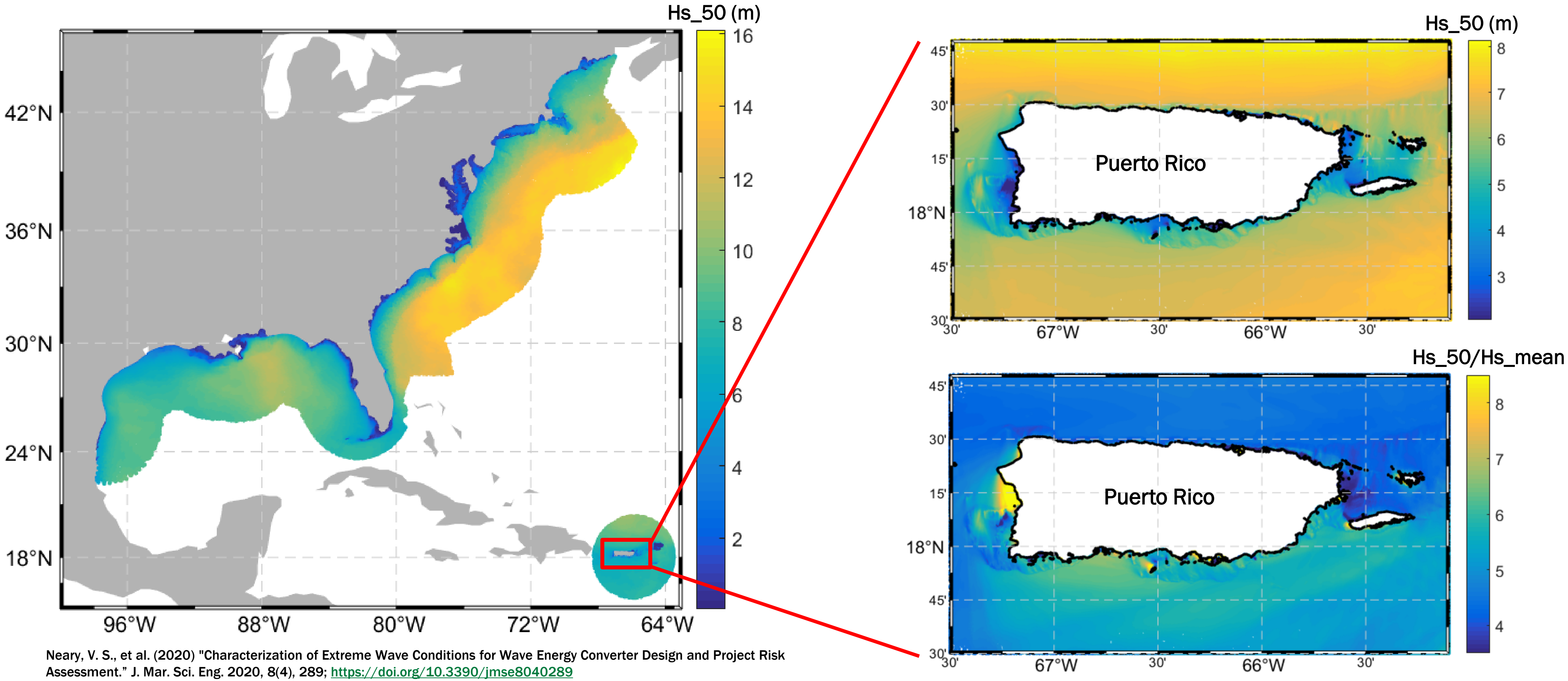
Powering the Blue Economy application – C wind seas

- Resonant period 6 s
- Low temporal variability
- Large directional spreading NE (winter) S (summer)

Ahn, S., Haas, K., and V.S. Neary (2020), Dominant wave energy systems and conditional wave resource characterizations for coastal waters of the United States, *Energies 2020, 13*(12), 3041; https://doi.org/10.3390/en13123041.

Extreme wave heights for characterizing wave loads (Neary et al. 2020)

Distribution of 50-year significant wave height, Hs(50), to characterize extreme wave loads along US East Coast



Neary, V. S., et al. (2020) "Characterization of Extreme Wave Conditions for Wave Energy Converter Design and Project Risk Assessment." J. Mar. Sci. Eng. 2020, 8(4), 289; https://doi.org/10.3390/jmse8040289

Future Work

- PBE Resource Assessment – sites/regions identified by the Energy Transitions Initiative Partnership Project (ETIPP)
- Site characterization measurements for utility-scale tidal energy development
- Global Wave Resource Dataset
- Ocean Current (Gulf Stream) Resource Modeling
- Tidal Resource Modeling
  - Alaska: Aleutian Islands, Southeast Alaska, Prince William Sound, Kodiak
  - Technical Resource Assessments
  - Piscataqua River and Columbia River
- IEC TC 114, Advisory Group 2 (AG2), Marine Energy Classification Sub-Team, 12 SMEs across 5 national committees charged with establishing consensus-based resource and device classification systems and incorporating them into relevant technical specifications over the next 2-3 years. Chair V.S. Neary, Vice-chair K.A. Haas.
- TurbSim Evaluation & Upgrade

Publications in preparation

1. Refined Wave Resource Assessment of the U.S., *Kilcher, Garcia-Medina, Yang*
2. Resource assessment of Western Passage, Maine, *Fogarty, Kilcher, et.al.,*
3. Tidal energy resource characterization following IEC standards – a case study in Tacoma Narrow, WA, Deb et al. 2022
4. Tidal turbulence modeling to aid marine renewable energy resource characterization: A case study in Western Passage, USA. Deb, Yang, Wang, Kilcher
5. Investigation of tidal energy resource assessment estimates and associated assumptions using numerical modeling, Falcone et al. 2022.
6. Characterizing the tidal hydrodynamics and resource in a tidal inlet to support marine energy research, Wang et al. 2022, to be submitted to Renewable Energy
7. Nearshore wave climate and energy resources in American Samoa, Garcia-Medina et al. 2022
8. Characterization of wave climate for Guam and the Northern Mariana Islands, Li et al. 2022
9. Wave climate and potential for wave energy harvesting in the U.S. Minor Outlying Islands, Garcia-Medina et al. 2022
10. Tidal energy resource classification system, Haas, Singh, Neary, Jang, July 2022, Submit to *Ren. Energy*.
11. Marine energy classification systems, Neary, Haas, Ahn, Colby, July 2022, Submit to *Ren. Energy*.

Publications

2022

- Ahn, S.; Neary, V.S., Allahdadi, M.; He, R. Feasibility-level validation of an ultra-high-resolution wave hindcast model for the Gulf of Mexico, Puerto Rico, and the U.S. Virgin Islands. Ocean Engineering, Submitted 19 September 2021. Revised Submission In Review
- Allahdadi, M., He, R., Neary, V.S. Revisiting effects of the Gulf Stream on ocean waves. Journal of Geophysical Research - Oceans. Revised Submission In Review.
- Ahn, S., V.S. Neary, and K.A. Haas, Global wave energy resource classification system for regional energy planning and project development. Renewable and Sustainable Energy Reviews, 2022. 162: p. 112438. https://doi.org/10.1016/j.rser.2022.112438
- Ahn, S., Neary, V.S., Allahdadi, M.N., R. He. High-resolution wave model hindcast of the Gulf of Mexico for investigating wave energy climate and non-stationary trends, AGU Ocean Sciences Meeting 2022, Honolulu, HI, 27 February – 4 March 2022.
- Allahdadi, M.N., He, R., V.S. Neary. Modulation of ocean waves by the Gulf Stream and its effects on the wave energy resource. AGU Ocean Sciences Meeting 2022, Honolulu, HI, 27 February – 4 March 2022.

2021

- Kilcher, Levi, Michelle Fogarty, and Michael Lawson. 2021. *Marine Energy in the United States: An Overview of Opportunities*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-78773. https://www.nrel.gov/docs/fy21osti/78773.pdf.
- Allahdadi, M.; He, R.; Ahn, S.; Chartrand, C.; Neary, V.S. (2021). Development and calibration of a high-resolution model for the Gulf of Mexico, Puerto Rico, and the U.S. Virgin Islands: Implication for wave energy resource characterization. Ocean Engineering, 2021. 235, 109304. DOI: 10.1016/j.oceaneng.2021.109304
- Ahn, S., Neary, V.S., Allahdadi, M., He, R., Nearshore wave energy resource characterization along the East Coast of the United States. Renewable Energy, 2021. 172: p. 1212-1224. https://doi.org/10.1016/j.renene.2021.03.037
- Ahn, S. and V. S. Neary. Wave energy resource characterization employing joint distributions in frequency-direction-time domain. *Applied Energy, 2021, 285: 116407.* https://doi.org/10.1016/j.apenergy.2020.116407
- Jang, M., Haas, K.A., Neary, V.S. A Characterization of tidal current velocity profiles for hydrokinetic energy conversion, iPoster, AGU Fall Meeting, New Orleans, LA, December 13-17, 2021.
- Ruhl, C., Banerjee, A., Chamorro, L.P., Neary, V.S. A Comparison of Turbulence Characteristics at Six Tidal Energy Sites, iPoster, AGU Fall Meeting, New Orleans, LA, December 13-17, 2021.
- Ruhl, C., Banerjee, A., Chamorro, L.P., Neary, V.S. A Survey of Turbulence Characteristics at Six Tidal Energy Sites, 74th Annual Meeting of the APS Division of Fluid Dynamics, Phoenix, AZ, November 21-23, 2021.
- Neary, V.S., K. A. Haas, J. Colby, “Type Classification for Tidal and Wave Energy Converters,” Abstract and video presentation at International Conference Ocean Energy 2021 (ICOE 2021), 28-30 April, 2021, Virtual conference hosted by US.
- Haas, K.A., Singh, S., Neary, V.S., M. Jang. Tidal energy resource assessment classification system. Abstract and video presentation at International Conference Ocean Energy 2021 (ICOE 2021), 28-30 April, 2021, Virtual conference hosted by US.

Publications (continued)

2020

- “A Tidal Hydrodynamic Model for Cook Inlet, Alaska, to Support Tidal Energy Resource Characterization”, Wang and Yang, JMSE (2020).
- “Characteristics and Variability of the Nearshore Wave Resource on the U.S. West Coast”, Yang, Garcia-Medina, Wu, and Wang, Energy (2020).
- “Development and validation of a high-resolution regional wave hindcast model for U.S. West Coast wave resource characterization”. Wu, Wang, Yang, García-Medina, Renewable Energy (2020)
- “Modeling Assessment of Tidal Energy Extraction in Western Passage”, Yang, Wang, Xiao, Kilcher, Haas, Xue, Feng, JMSE (2020).
- “Characterization of extreme wave conditions for wave energy converter design and project risk assessment,” Neary, Ahn, Seng, Allahdadi, Wang, Yang, He, JMSE (2020).
- Yang, Z. and V.S. Neary, High-resolution hindcasts for U.S. wave energy resource characterization. International Marine Energy Journal 2020, 3, 65-71, https://doi.org/10.36688/imej.3.65-71.
- Ahn, S.; Neary, V.S. Non-stationary historical trends in wave energy climate for coastal waters of the United States. Ocean Engineering 2020, 216, https://doi.org/10.1016/j.oceaneng.2020.108044.
- Ahn, S., Haas, K., and V.S. Neary (2020), Dominant wave energy systems and conditional wave resource characterizations for coastal waters of the United States, *Energies 2020, 13*(12), 3041; https://doi.org/10.3390/en13123041.
- Neary, V. S., S. Ahn, B. E. Seng, M. N. Allahdadi, T. Wang, Z. Yang and R. He (2020). "Characterization of Extreme Wave Conditions for Wave Energy Converter Design and Project Risk Assessment.” *J. Mar. Sci. Eng.* 2020, 8(4), 289; https://doi.org/10.3390/jmse8040289.
- Ahn, S., Haas, K., and V.S. Neary (2020), Wave energy resource characterization and assessment for coastal waters of the United States, *Applied Energy,* 104, 54-68. https://doi.org/10.1016/j.apenergy.2020.114922.
- Haas, K.A., V. S. Neary, S. Singh, M. Jang, “Tidal energy resource classification system,” Asian Wave and Tidal Energy Conference (AWTEC), Virtual Conference, Hobart, Tasmania, Australia, 8-12 November 2020

2019

- Allahdadi, M. N., He, R., and Neary, V. S.: Predicting ocean waves along the US East Coast during energetic winter storms: sensitivity to whitecapping parameterizations, *Ocean Sci.*, 15, 691-715, https://doi.org/10.5194/os-15-691-2019, 2019.
- Ahn, S., Haas, K., and V.S. Neary (2019), Wave energy resource classification system for US coastal waters, *Renewable and Sustainable Energy Reviews,* 104, 54-68. https://doi.org/10.1016/j.rser.2019.01.017
- Allahdadi, M.N., Gunawan, J. Lai, R. He, V.S. Neary (2019), Development and validation of a regional-scale high-resolution unstructured model for wave energy resource characterization along the US East Coast, *Renewable Energy* 136, 500-511. https://doi.org/10.1016/j.renene.2019.01.020
- L. F. Kilcher, V. S. Neary, Z. Yang, “Marine energy characterization and classification in the United States,” European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019
- Neary, V.S., K. A. Haas, J. Colby, “Marine Energy Classification Systems: Tools for resource assessment and design,” European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019.

Publications (continued)

2019 (continued)

- K. A. Haas, S. Ahn, V. S. Neary, "Wave energy resource classification system as characterization and assessment tool," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019
- Z. Yang, V. S. Neary, "U.S. regional wave model hindcasts for wave resource characterization, classification and assessment," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019
- Neary, V.S., B. E. Seng, Z. Yang, N. Allahdadi, R. He, T. Wang, "Model performance predicting extreme wave heights for project risk assessment and WEC design," European Wave and Tidal Energy Conference (EWTEC), Naples, Italy, 2019.

2018

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