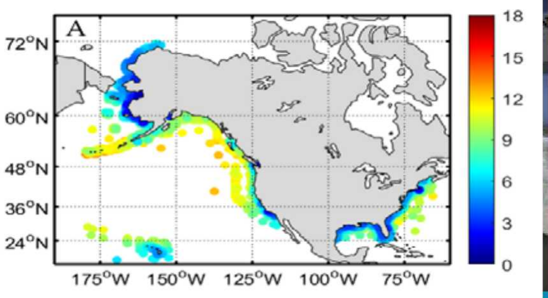
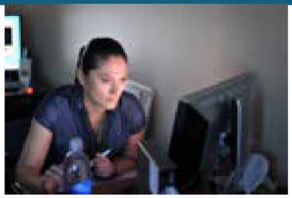
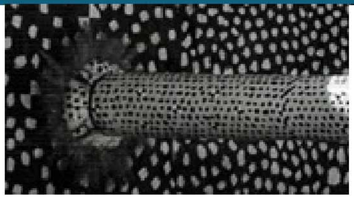
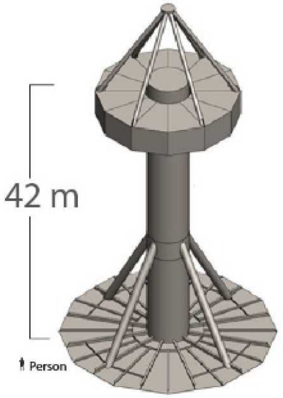
SAND2019-12769PE

Advancing marine renewable energy technologies to commercialization: Opportunities & challenges









PRESENTED BY

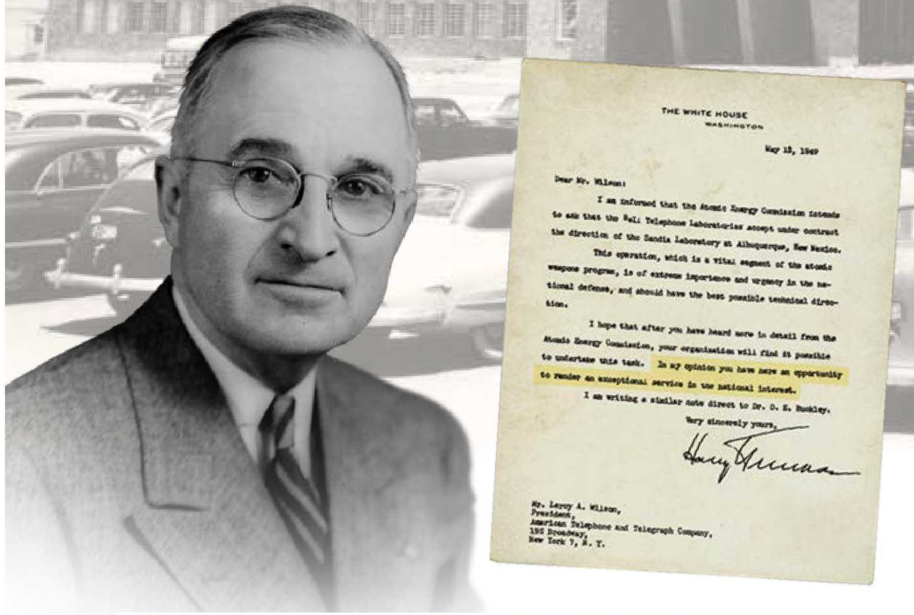
Vincent Neary, Water Power Technologies, 30 October 2019

Cyber Physical Infrastructure and Energy Horizons Distinguished Seminar

SAND2019-XXXX

Sandia National Laboratories: Background

"…exceptional service in the national interest."
President Truman 1949


THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

Manhattan Project's Engineering Division, est.1945

Federally Funded Research & Development Center (FFRDC) for the National Nuclear Security Administration (NNSA) of the US Department of Energy (USDOE)

Annual budget over $3.6 billion, FY18

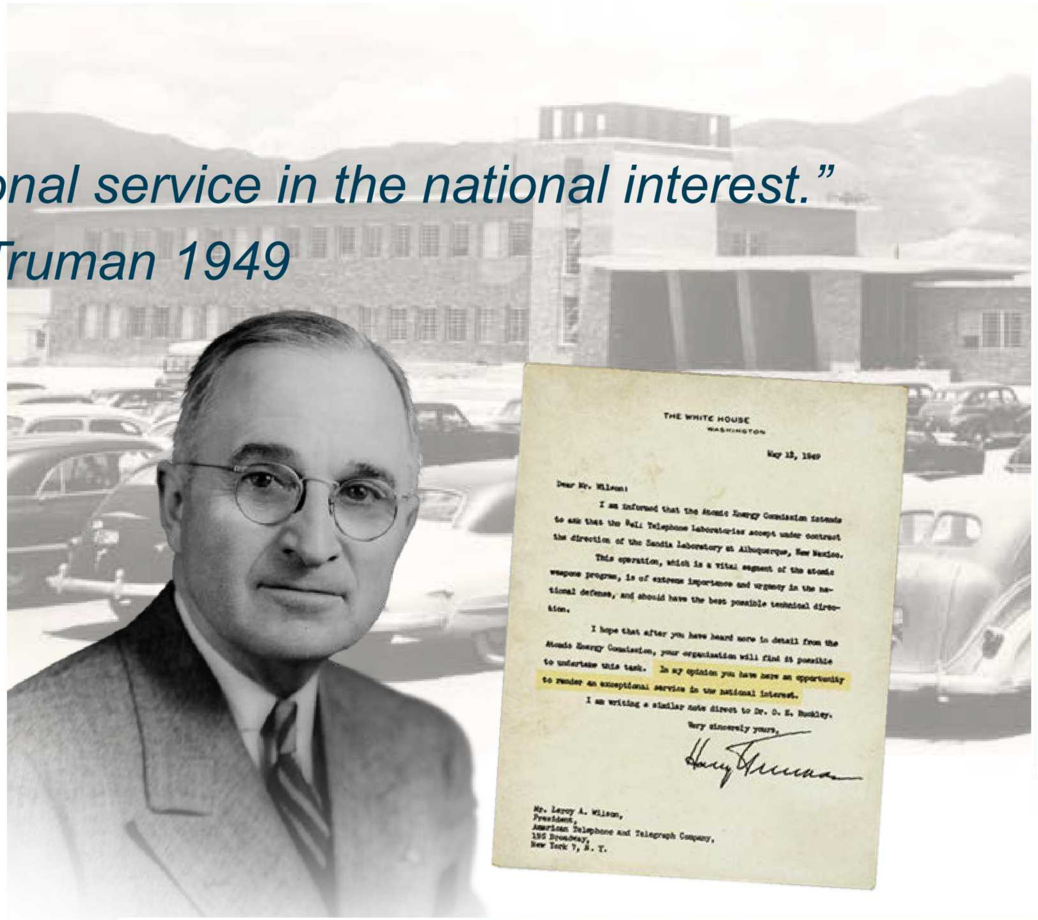
Over 13,000 full time staff

50% of technical staff with advanced engineering degrees

Sandia National Laboratories

Sandia National Laboratories: Securing Our Nation's Future

"…exceptional service in the national interest."
President Truman 1949



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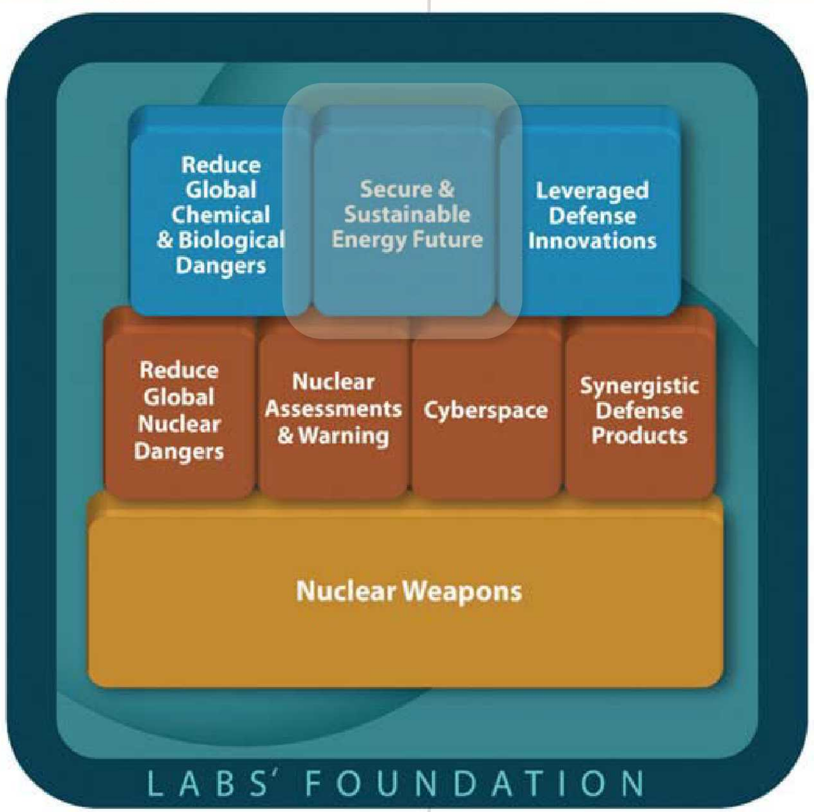
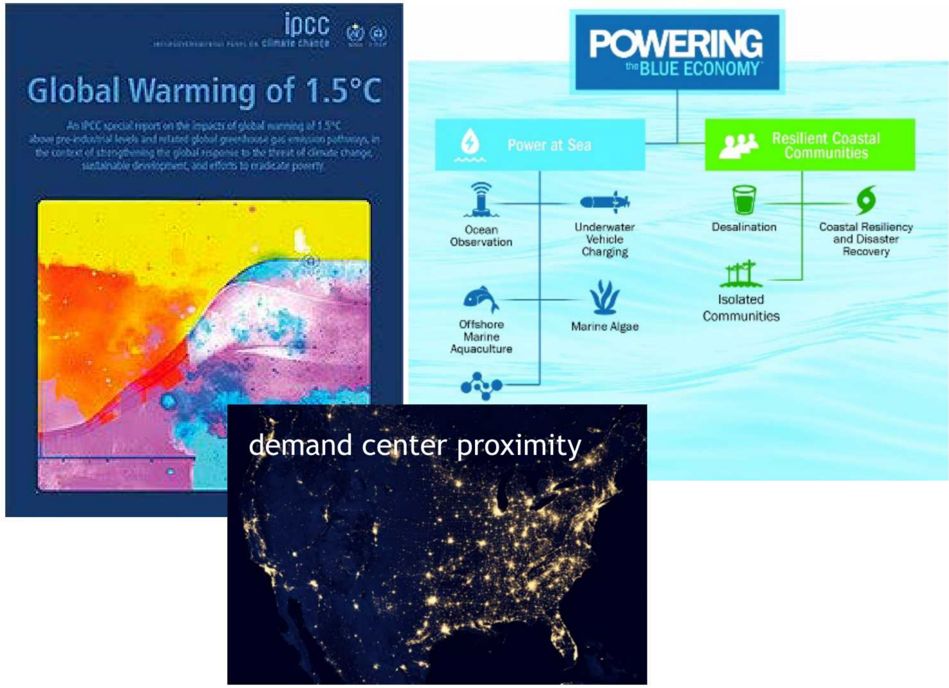


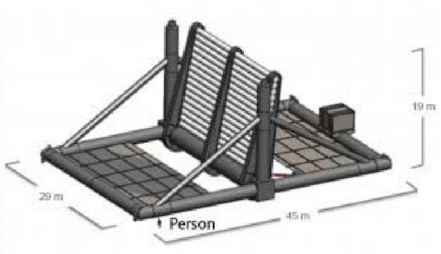
Non-NNSA DOE funding FY18, $266 million, includes $87 million from Energy Efficiency and Renewable Energy (EERE) Office

Sandia National Laboratories

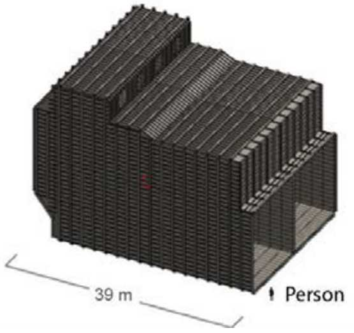
Marine renewable energy: Opportunities & challenges

Marine renewable energy; Opportunities and challenges

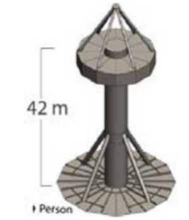




RM5, 10 MW, 0.87€ /kWh



RM6, 10 MW, 1.35€/kWh



RM3, 10 MW, 0.87€/kWh

USDOE's Reference Model WECs [Neary et al. 2013]

Opportunities

Urgency to move to renewable energy dominant portfolios [IPCC 2018]

Large power densities close to population centers [NASA 2012]

Blue economy – local energy sources for maritime markets, e.g., desalinization, aquaculture, observation & navigation[USDOE 2019]

Challenges

Difficult engineering - Harsh marine environment

High capital, installation, operation and maintenance (IO&M) costs [Neary et al. 2013]

Infrastructure for testing and IO&M

Complex and costly permitting process

Market opportunities unclear, and no established supply chains

USDOE R&D Program

2015 LCOE
~$1.20/kWh

Technology development

- Early stage concepts
- Component & subsystem innovations
- Test infrastructure
- **Open source models/tools**
- Demonstration projects
- **Performance & LCOE assessment**

Resource characterization & assessment

- National resource and regional distribution
- **Resource statistics characterizing average and extreme conditions**

Market acceleration

- Potential markets and supply chains
- Environmental compliance
- Stakeholder/user conflict avoidance and mitigation
- Standards and certification

2030 Target LCOE
~$0.12/kWh

Reference model project to benchmark LCOE

Levelized Cost of Energy (LCOE)

Levelized Cost of Electricity

- Denotes "Break Even" cost assuming minimum rate of return.

$$LCOE = \frac{(FCR \times CapEx) + OpEx}{AEP}$$

Reducing LCOE

- CapEx
  - Development costs, Infrastructure, Mooring/Foundation, Device Structural Components, Power Take Off (PTO), Subsystem Integration & Profit Margin, Installation, Contingency
- OpEx
  - Marine Operations & Maintenance (O&M), Shore-side Operations & Maintenance (O&M), Post Installation Environmental O&M, Replacement Parts, Consumables, Insurance

Increasing AEP

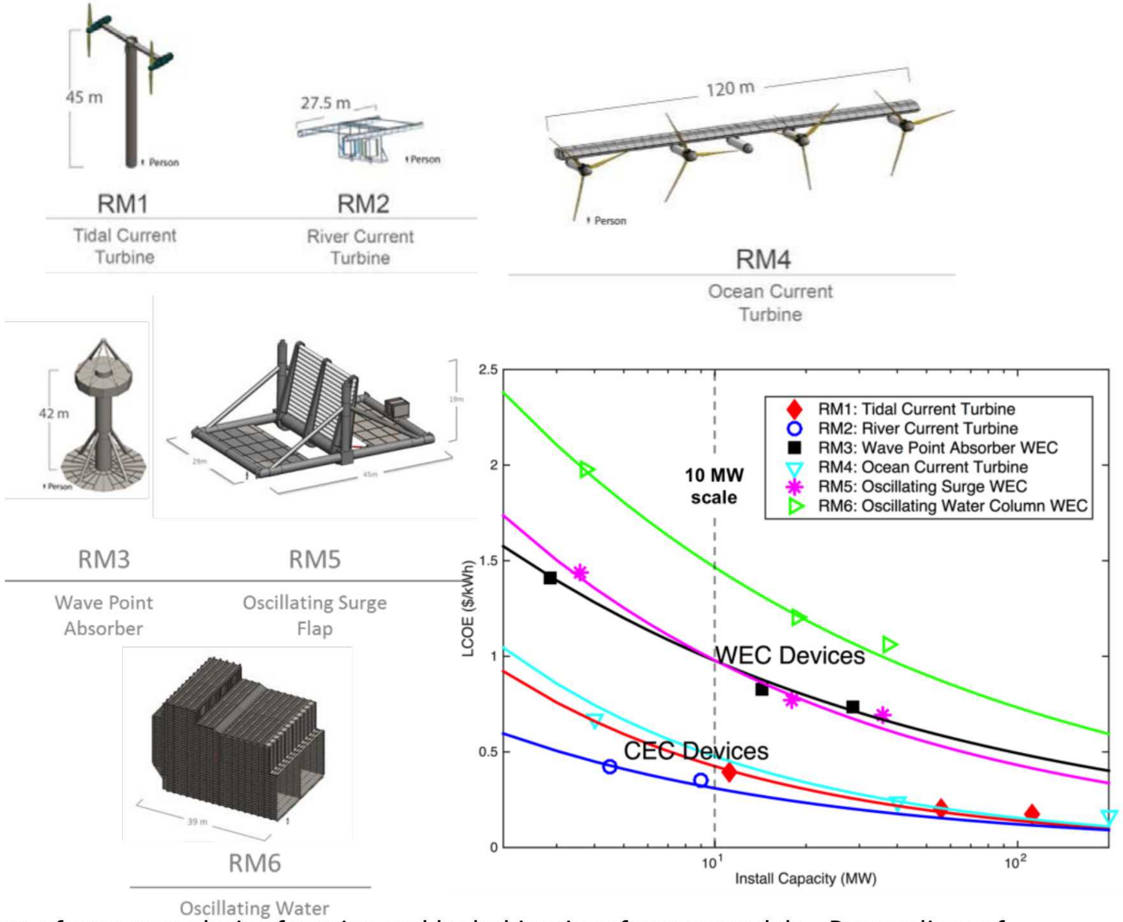
- Technical performance
- Resource attributes
- Operational reliability

Reference model project: Benchmarking LCOE

Reference Model Project

Benchmarked LCOE & identified cost drivers

- CECs – 10 MW Projects
  - ≈ $0.31-0.45/kWh
  - Cost drivers PTO, structure, O&M
- WECs – 10 MW Projects
  - $0.98/kWh for RM3, RM5
  - $1.53/kWh for RM6
  - Cost drivers structure, mooring, O&M

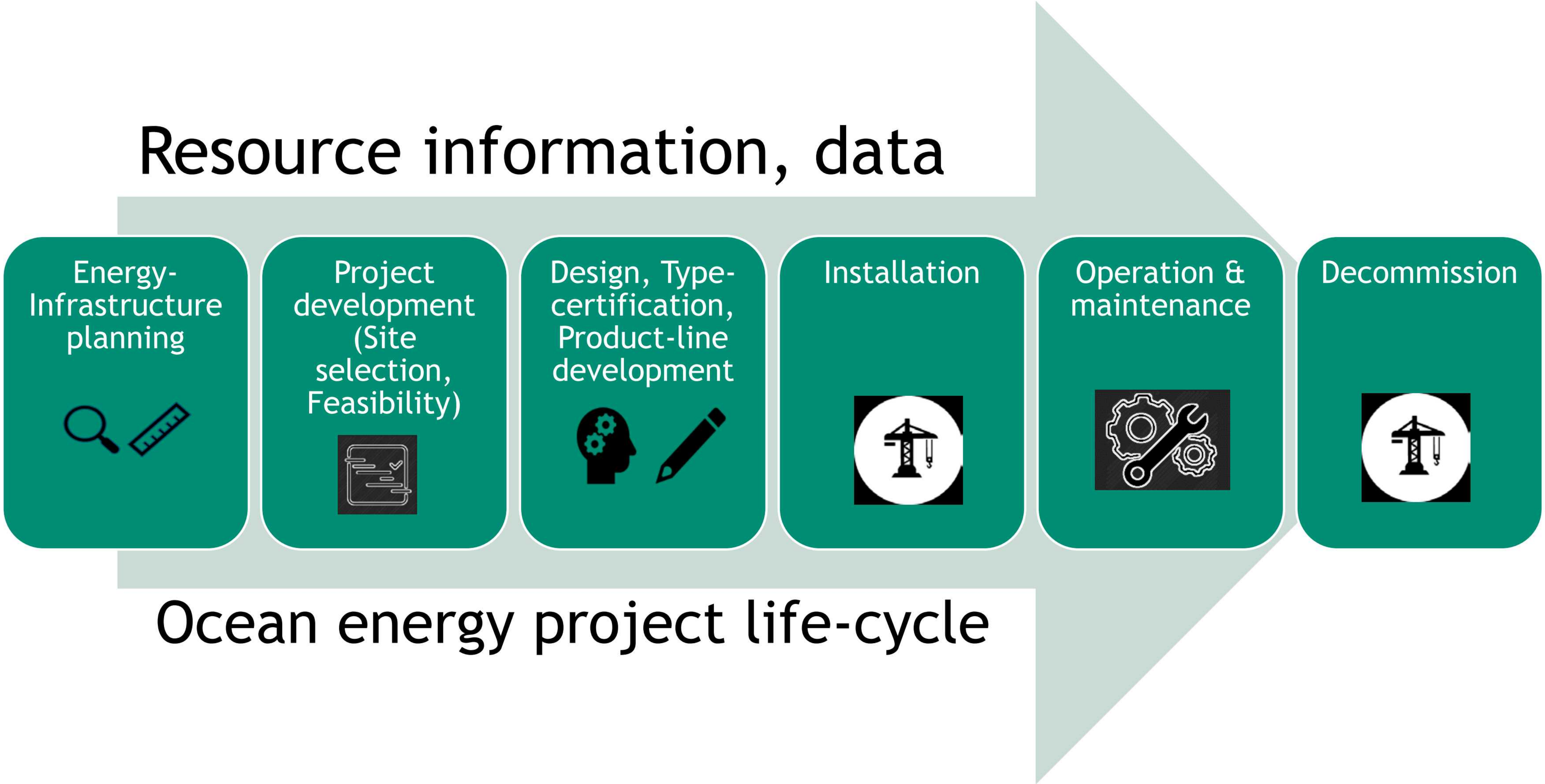


Jenne, D.S., Yi-Hsiang, Y. and V.S. Neary, (2015). Levelized cost of energy analysis of marine and hydrokinetic reference models. Proceedings of 3rd Annual Marine Energy Technology Symposium 2015 (METS2015), Washington, D.C., April 27-29.

Open source models and tools

Resource characterization & assessment (wave resource)

Resource characterization needs in project life cycle



Background

- National resource assessments quantified potential contribution of wave energy to electricity production nationally and regionally [EPRI 2011, Chawla et al. 2013]
- More refined and comprehensive characterization needed to support energy planning, project development and WEC design
- Three assessment levels (area, Δx, Δt)
  - Reconnaissance (>300 km), 5 km, 3 h ☑
  - Feasibility (20-500 km), 500 m, 3 h ☐
  - Design (<25 km), 50 m, 1 h ☐

The MHK Atlas wave power density map.
Source:[NREL 2019].https://maps.nrel.gov/mhk-atlas/

Resource	Theoretical Resource
Waves	**2,000 TWh/year**
Tidal streams	445 TWh/year
Ocean currents	200 TWh/year

Source: USDOE 2015 Quadrennial Technology Review, http://energy.gov/qtr

Goals/Objectives

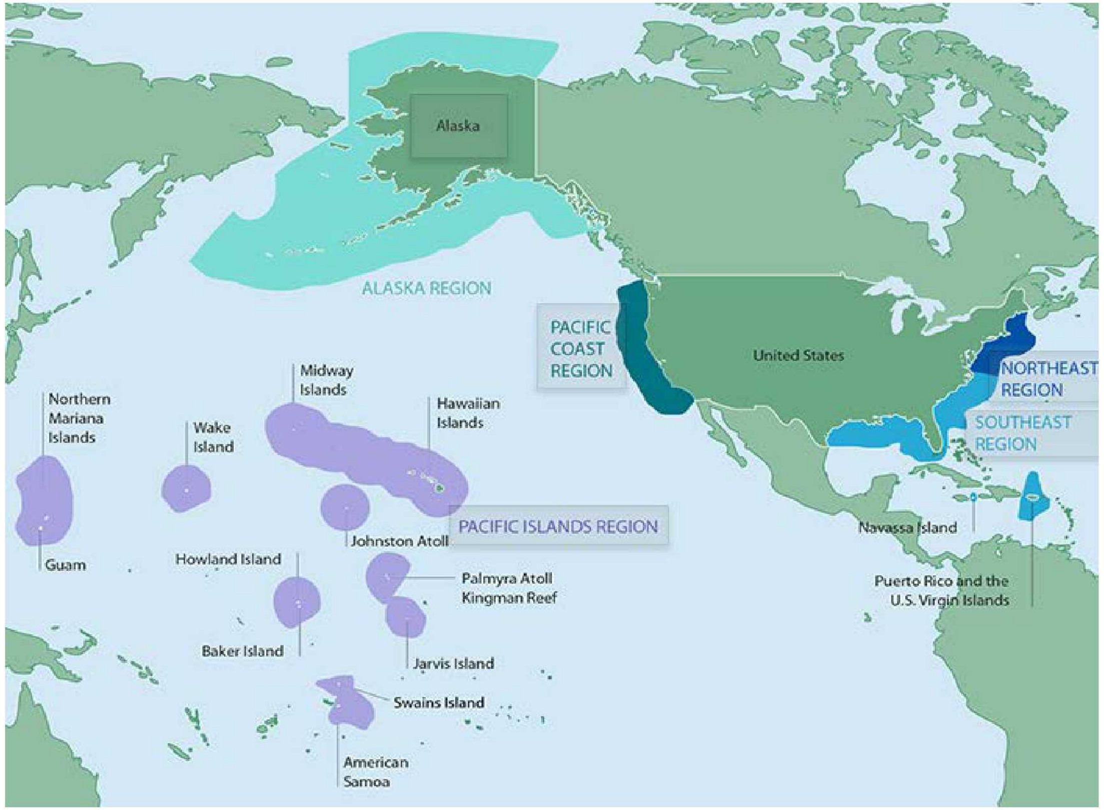
Generate high-resolution resource data source covering all US economic exclusion zones (EEZ) from 32-40 year wave model hindcast

Improve data source ☑

Characterize resource attributes ☑

Disseminate data and information ☑

Region	Area, km^2	Status
West Coast	825,549	Complete
East Coast	915,763	Complete
Alaska	3,770,021	Complete
Hawaii Islands	1,579,538	2019
Gulf of Mexico	707,832	2019
Pacific Islands	3,328,925	2020
Puerto Rico, US Virgin Islands	211,429	2020



US Economic Exclusion Zones (EEZ)

U.S. EEZ consists of following sub-regions: (a) Pacific West Coast; (b) East Coast (Northeast and Southeast regions); (c) Alaska; (d) Gulf of Mexico; (e) Puerto Rico and U.S. Virgin Islands; (f) Hawaii and Pacific Islands. EEZ is defined as a sea zone that extends 370 km (200 nmi) offshore from its coastal baseline. The image is obtained from NOAA National Ocean Service. https://www.worldatlas.com/articles/countries-with-the-largest-exclusive-economic-zones.html

Methods: Spectral wave modeling (SWAN)

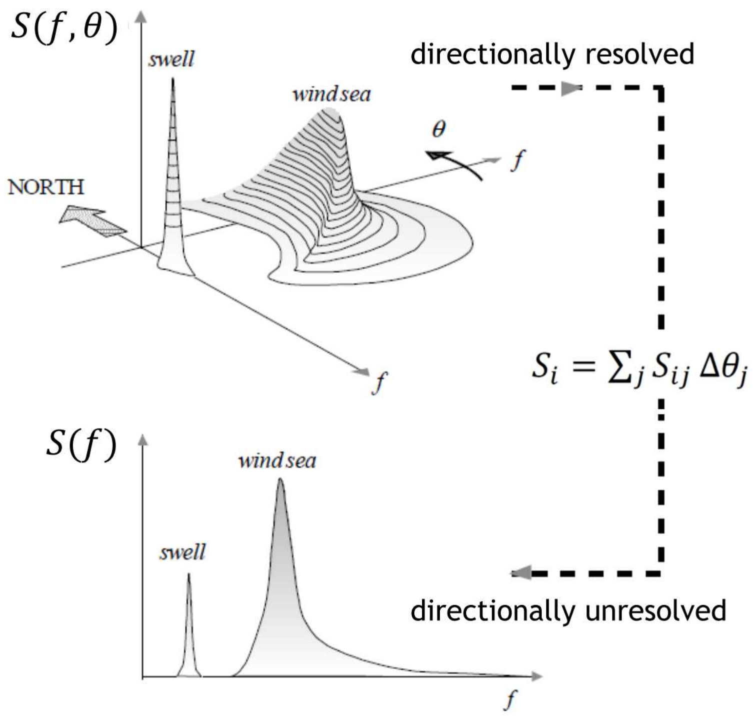
Emphasis on validated spectral wave model hindcast data

Evolution of wave action density (N) in space and time for all frequencies ($\sigma=2\pi f$) and directions (θ) (LHS)

Source and sink terms that generate, transfer and dissipate wave energy

Feasibility/Design level Δx = 200-300 m, Δt =1 h

Source: SWAN Technical Manual

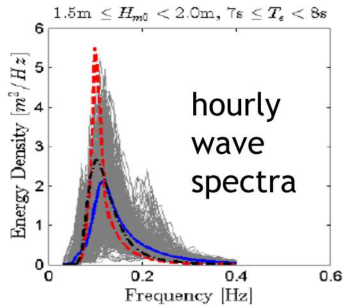


$$S_i = \sum_j S_{ij}\,\Delta\theta_j$$

$$N = S(f,\theta)/\sigma$$

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{\text{tot}}}{\sigma}$$

$$S_{\text{tot}} = S_{\text{in}} + S_{\text{nl3}} + S_{\text{nl4}} + S_{\text{ds,w}} + S_{\text{ds,b}} + S_{\text{ds,br}}$$



Resource metrics: IEC parameters [IEC TS 62600-101:2015-06]

Omnidirectional wave power, *J*

$$J = \rho g \sum_{i,j} c_{g,i} S_{ij}\, \Delta f_i \Delta\theta_j \quad \text{[kW/m]}$$

- Total wave energy flux at point of interest
- Directionally unresolved

Directionally resolved wave power, J_θ

$$J_\theta = \rho g \sum_{i,j} c_{g,i} S_{ij} \Delta f_i \Delta\theta_j \cos(\theta - \theta_j)\delta \quad \text{[kW/m]}$$

- Wave energy flux through vertical plane of unit width

Direction of max J_θ

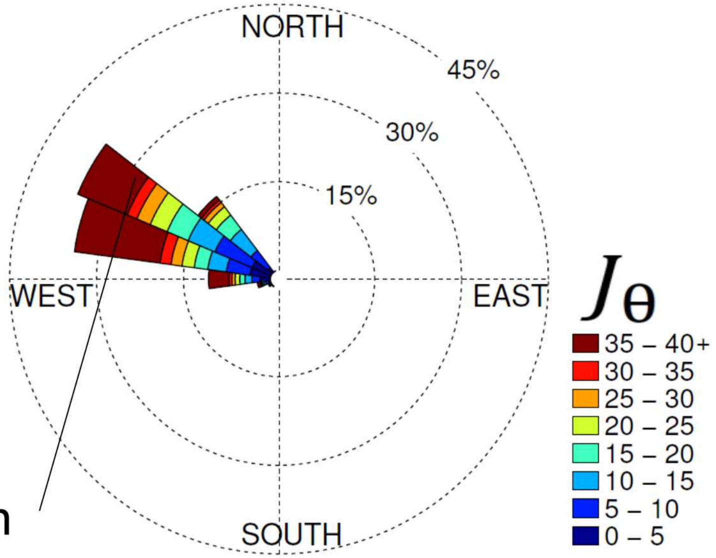
$$\theta_{\text{Jmax}} \quad \text{[deg]}$$

- Bearing where most of the incident wave power coming from

Directionality coefficient, *d*

$$d = \frac{J_{\theta_{\text{Jmax}}}}{J} \quad \text{[-]}$$

- Measure of directional spreading



$J_{\theta max}$ ~36 kW/m
θ_{Jmax} ~300 deg.

Resource metrics: IEC parameters [IEC TS 62600-101:2015-06]

Spectral moments

$$m_n = \sum_i f_i^n S_i \Delta f_i$$

- Used to derive important wave statistics

Significant wave height

$$H_{m0} = 4\sqrt{m_0} \qquad [m]$$

- Proxy for H_s, combined with T_e to define sea states in scatter plots

Energy period

$$T_e \equiv T_{-10} = \frac{m_{-1}}{m_0} \qquad [s]$$

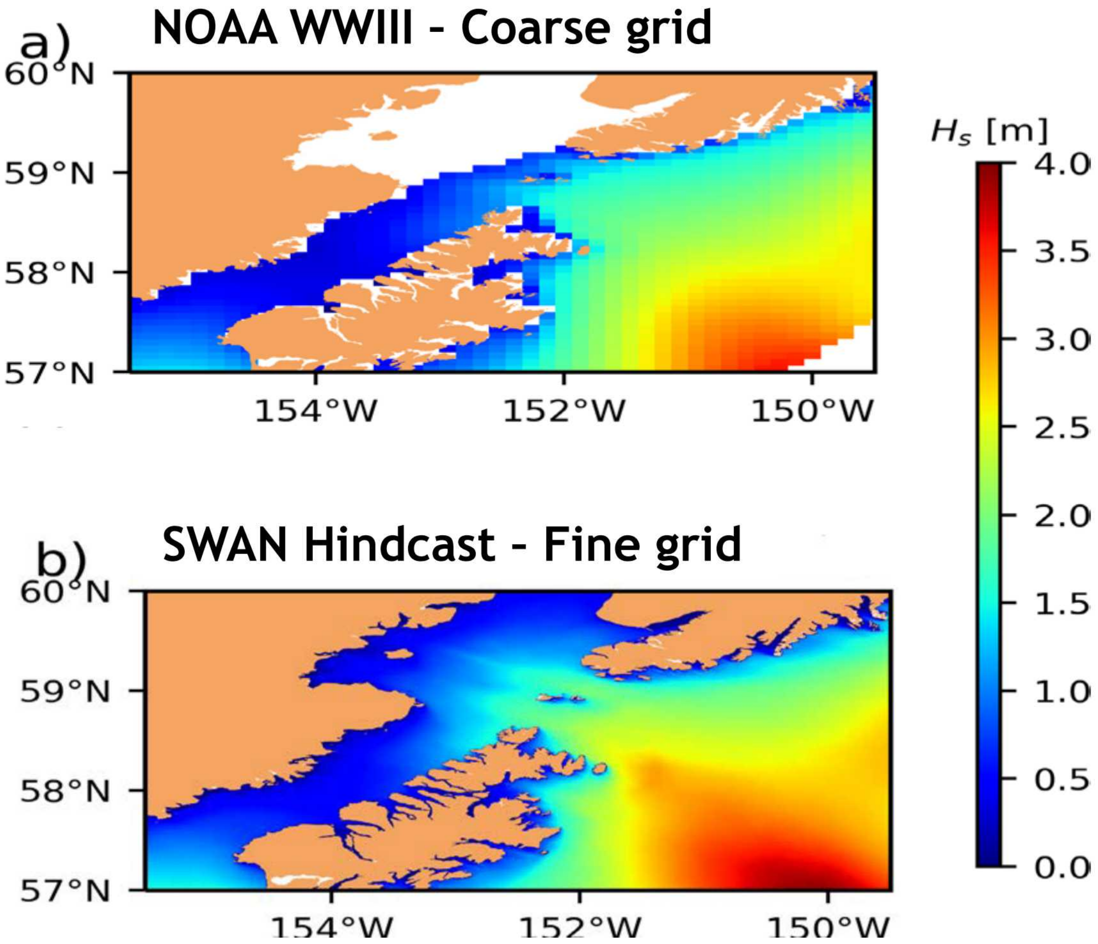
- Centroid of wave power spectrum, with H_{mo} to define sea states in scatter plots

Spectral width

$$\epsilon_0 = \sqrt{\frac{m_0 m_{-2}}{m_{-1}^2} - 1} \qquad [-]$$

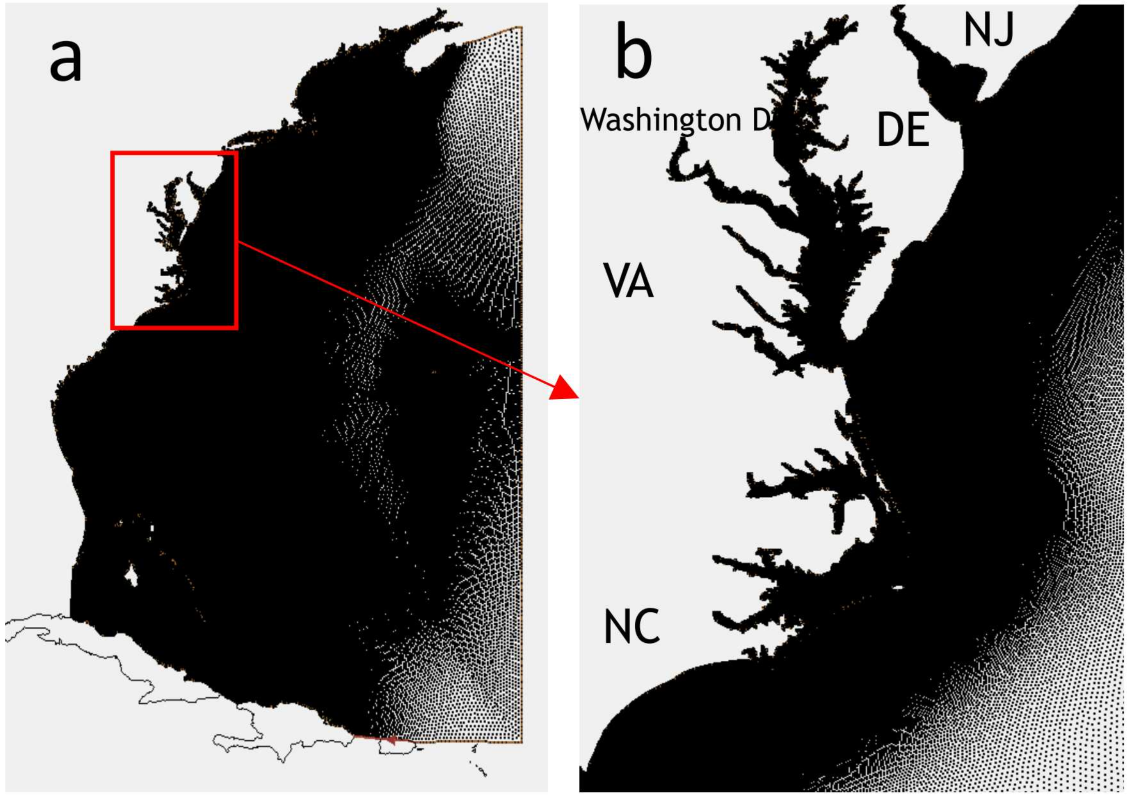
- Characterizes energy spreading in wave spectrum.

Results: Model mesh refinement [Yang & Neary 2019]



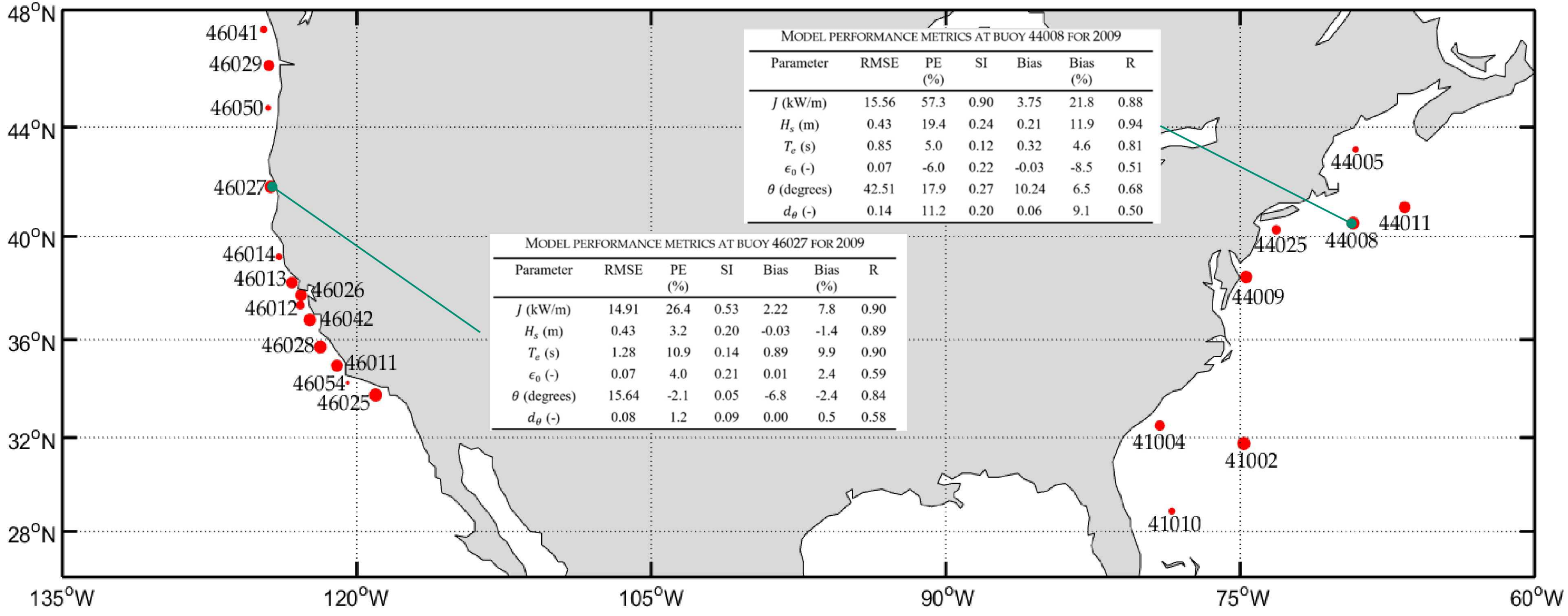
Significant wave height near Kodiak, Alaska, simulated by NOAA WWIII (a) and UnSWAN (b) [Yang & Neary 2019]

SWAN East Coast Region Hindcast



SWAN model grid for U.S. East Coast (a) and zoomed-in near the Chesapeake Bay region (b) [Allahdadi et al. 2019, Yang & Neary 2019]

Results: Better accuracy, IEC metrics [Yang et al. 2017; Allhadadi et al. 2019; Yang and Neary 2019]



MODEL PERFORMANCE METRICS AT BUOY 44008 FOR 2009

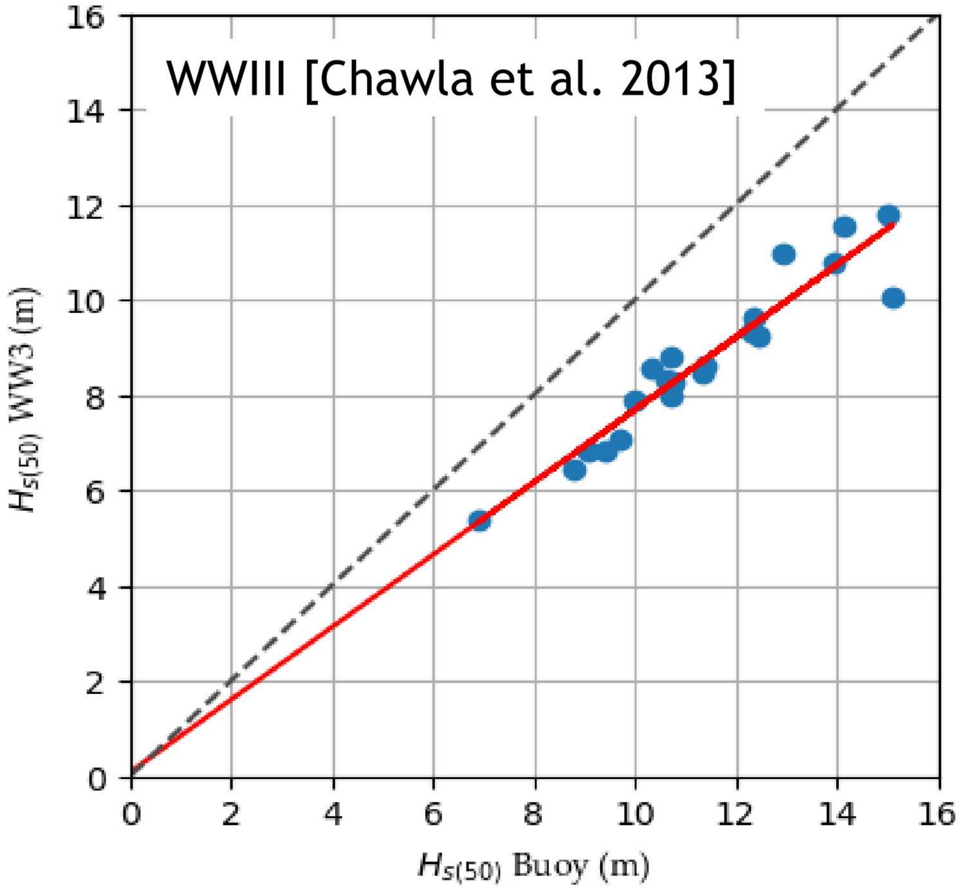
Parameter	RMSE	PE (%)	SI	Bias	Bias (%)	R
J (kW/m)	15.56	57.3	0.90	3.75	21.8	0.88
H_s (m)	0.43	19.4	0.24	0.21	11.9	0.94
T_e (s)	0.85	5.0	0.12	0.32	4.6	0.81
ϵ_0 (-)	0.07	-6.0	0.22	-0.03	-8.5	0.51
θ (degrees)	42.51	17.9	0.27	10.24	6.5	0.68
d_θ (-)	0.14	11.2	0.20	0.06	9.1	0.50

MODEL PERFORMANCE METRICS AT BUOY 46027 FOR 2009

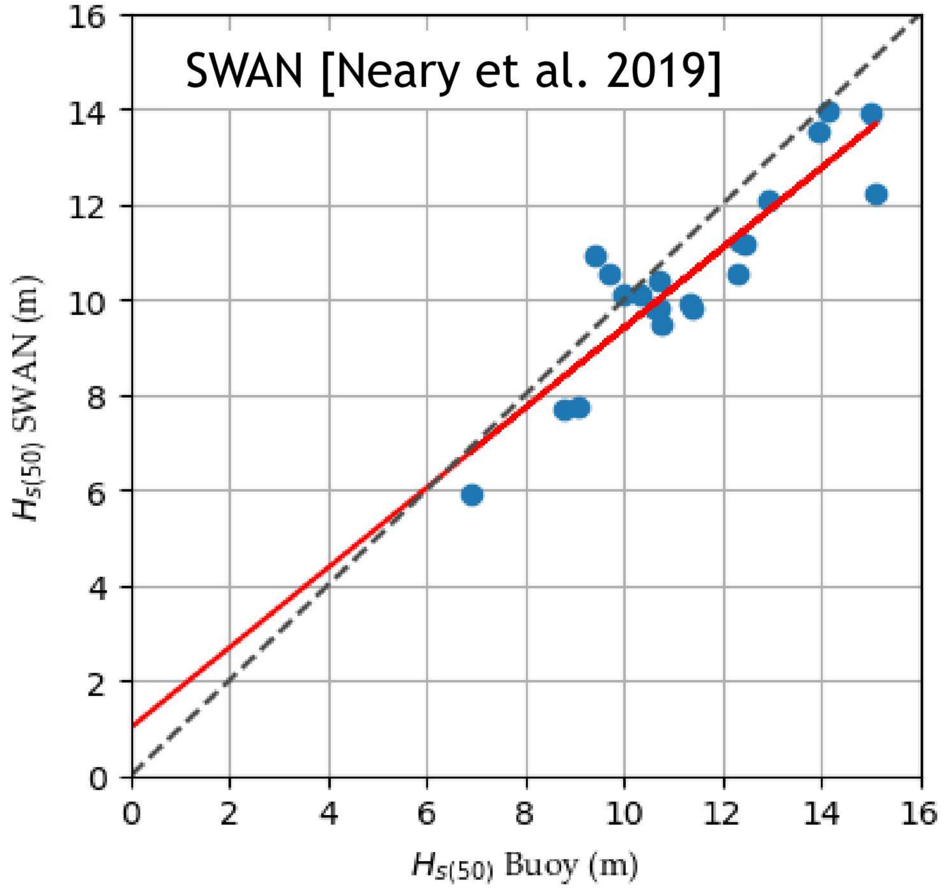
Parameter	RMSE	PE (%)	SI	Bias	Bias (%)	R
J (kW/m)	14.91	26.4	0.53	2.22	7.8	0.90
H_s (m)	0.43	3.2	0.20	-0.03	-1.4	0.89
T_e (s)	1.28	10.9	0.14	0.89	9.9	0.90
ϵ_0 (-)	0.07	4.0	0.21	0.01	2.4	0.59
θ (degrees)	15.64	-2.1	0.05	-6.8	-2.4	0.84
d_θ (-)	0.08	1.2	0.09	0.00	0.5	0.58

Results: Better accuracy, $H_{s(50)}$ [Neary et al. 2019]

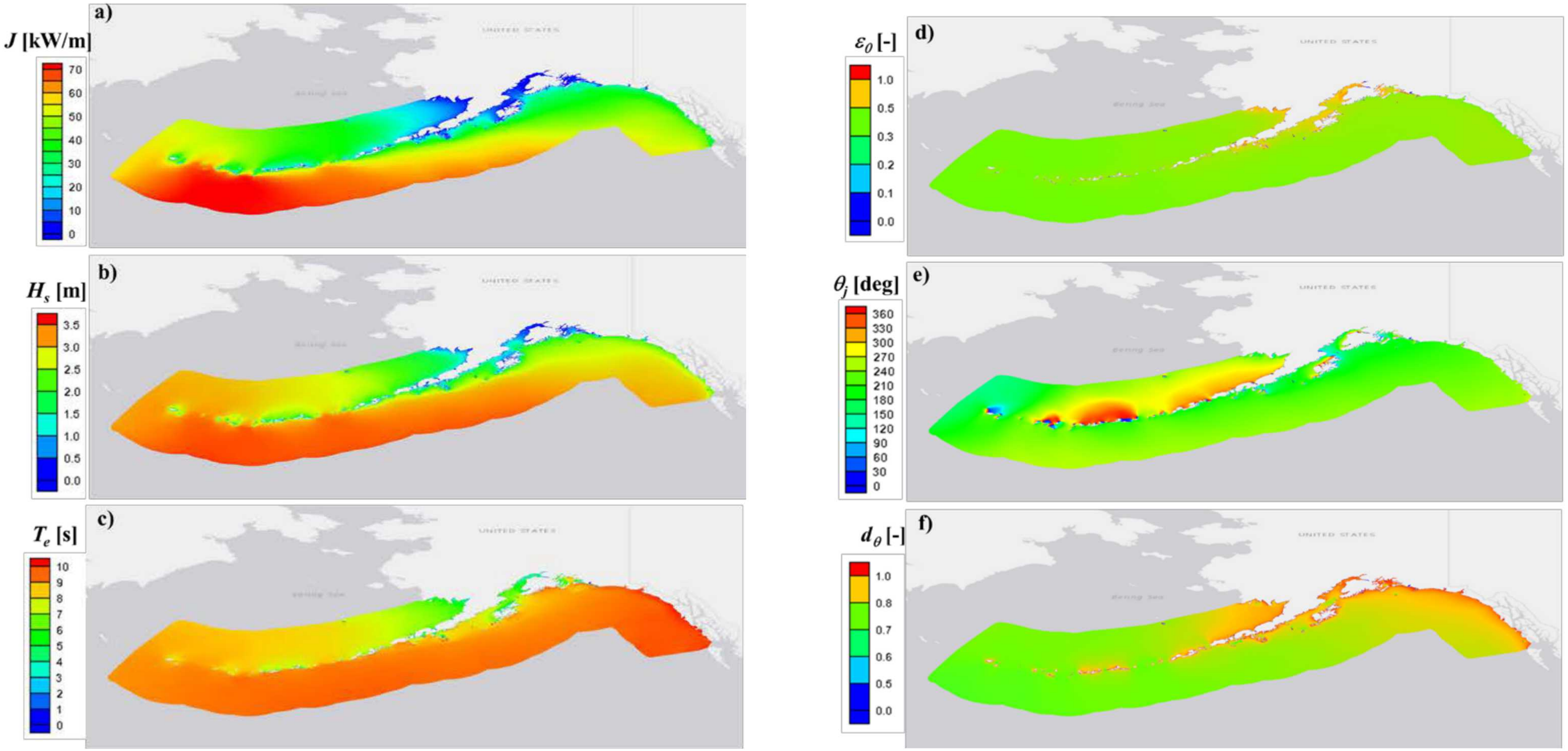
NOAA WWIII – Coarse grid



SWAN Regional- Fine grid



Results: 6 IEC parameters at 200-300 m resolution [Yang & Neary 2019]



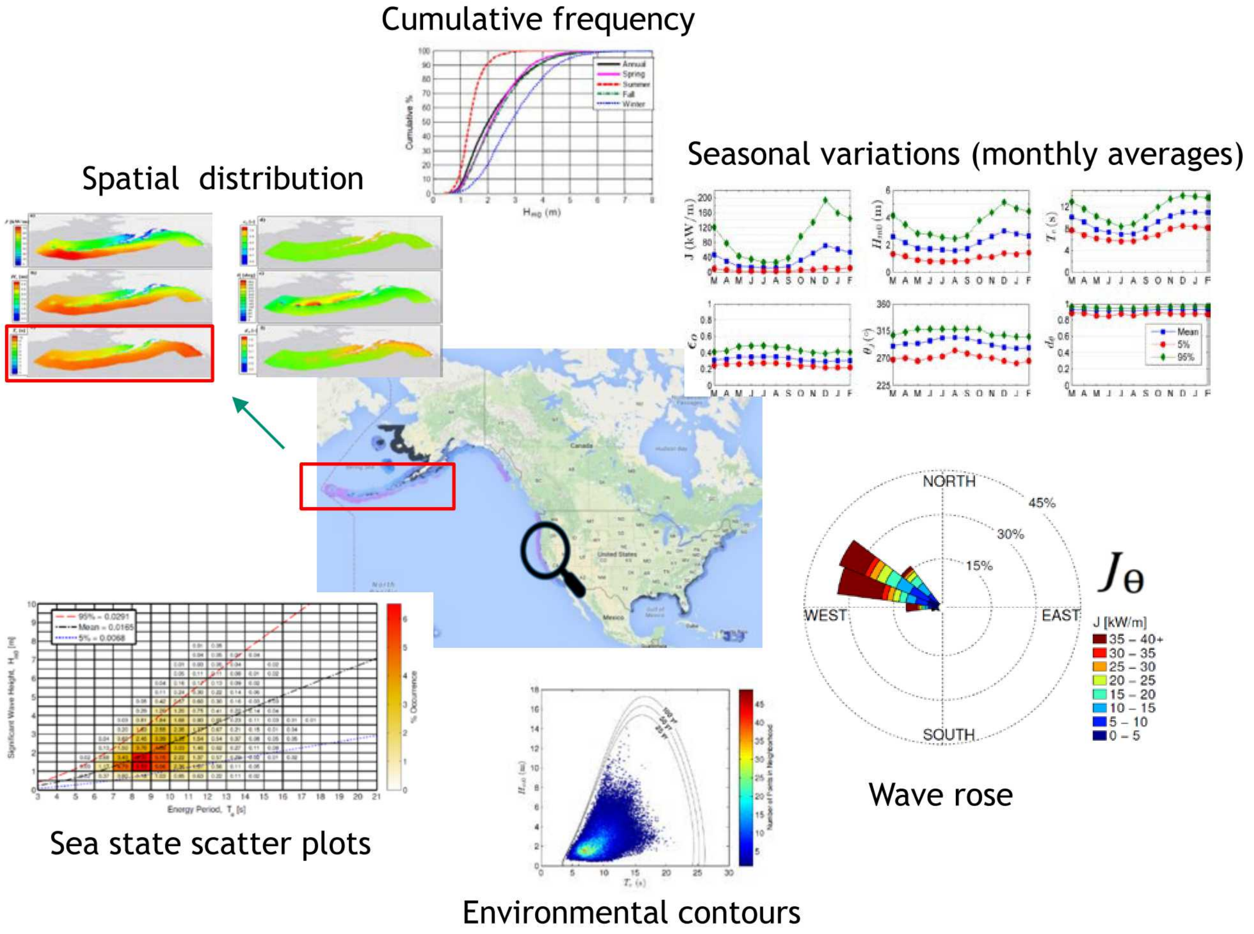
Simulated annual averages of six IEC metrics for year 2009 in Alaska region: (a) omnidirectional wave power; (b) significant wave height; (c) energy period; (d) spectral width; (e) direction of maximum directionally resolved wave power, and (f) directionality coefficient [Yang & Neary 2019]

Results: Resource data archiving & dissemination (In progress)

MHK ATLAS upgrade (In-progress)
- All 6 IEC parameters, monthly averages and average annual values
- Hs(50, 5, 1-year)
- 200-300 m resolution within US EEZ
- Includes shallow nearshore waters

MHK Data Repository (TBD)
- 2D spectra, *O*(100) points each region
- Partitioned bulk parameters, *O*(1,000) points each region
- IEC parameter time series, *O*(1M) points

Functional GIS dissemination platforms (TBD)
- Bureau of Ocean Energy Management (BOEM), US Dept. of Interior (USDOI)
- NOAA, Ocean Project Planning Tool,
- US Dept. of Commerce (USDOC)
- Private vendor, e.g., Open Ocean (Marine data intelligence) http://www.openocean.fr/en/



BOEM Bureau of Ocean Energy Management

U.S. DEPARTMENT OF ENERGY

NOAA National Oceanic and Atmospheric Administration U.S. Department of Commerce

Concluding remarks

US experience demonstrates trend towards improved resource characterization and assessment through:

- High-resolution wave model hindcasts validated with buoy measurements
- Improved data dissemination through functional GIS platforms (MHK Atlas) and on-line data repositories.

Ongoing R&D:

- Augmenting characterization with additional metrics
- Investigating inter-annual and non-stationary trends

Conclusions and recommendations for further work

An integrated systems approach is required to develop successful marine energy systems; therefore collaboration with industry and engagement with original equipment manufacturers from the early stage of development is recommended.

System capabilities and requirements should be properly defined and made transparent to increase the effectiveness of future emerging technologies development and applicability to ocean energy technologies.

The transferability of solutions from other sector, as well as the development of new technologies and materials could impact significantly on the speed of development of future emerging technologies for ocean energy.

The impact of the future emerging technologies should be put in the context of the priorities for the ocean energy sector as identified through the Ocean Energy Roadmap and the SET-Plan Implementation Plan.

A further analysis is needed to prioritise which options could have the greatest impact on the sector in achieving short-term goals (2025 targets) and long term ambitions (100 GW of installed capacity by 2050).

This report compiles the outcomes of an international workshop on emerging energy technologies held in March 2019.

Source: https://www.sciencedaily.com/releases/2018/10/181030174952.htm

ACKNOWLEDGEMENTS:

Contributors to this work include Sandia colleagues Bibiana Seng, Sara Bredin, Dr. Seongho Ahn; Pacific Northwest National Laboratory researchers Dr. Zhaoqing Yang, and Dr. Taiping Wang; Georgia Tech researcher Dr. Kevin Haas; and North Carolina State University researchers Dr. Nabi Allahdadi and Dr. Ruoying He. The model test bed study benefited from review and input from steering committee members including Dr. Bryson Robertson, University of Victoria, Dr. Arun Chawla of NOAA.

Thank you

Contact: vsneary@sandia.gov

Extra slides

Resource metrics: Extreme conditions [Neary et al. 2017, 2019]

Extreme wave height

$H_{s(50)}$	$H_{s(5)}$	$H_{s(1)}$	[m]

- Characterizes wave load [DNV RP-C205 2014]

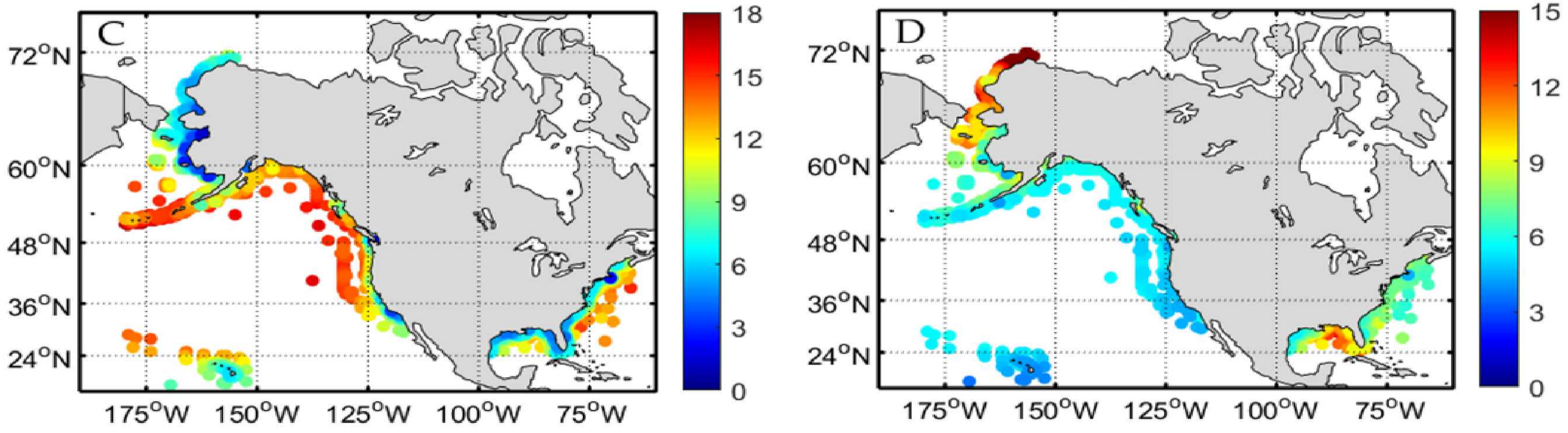
Relative risk ratio

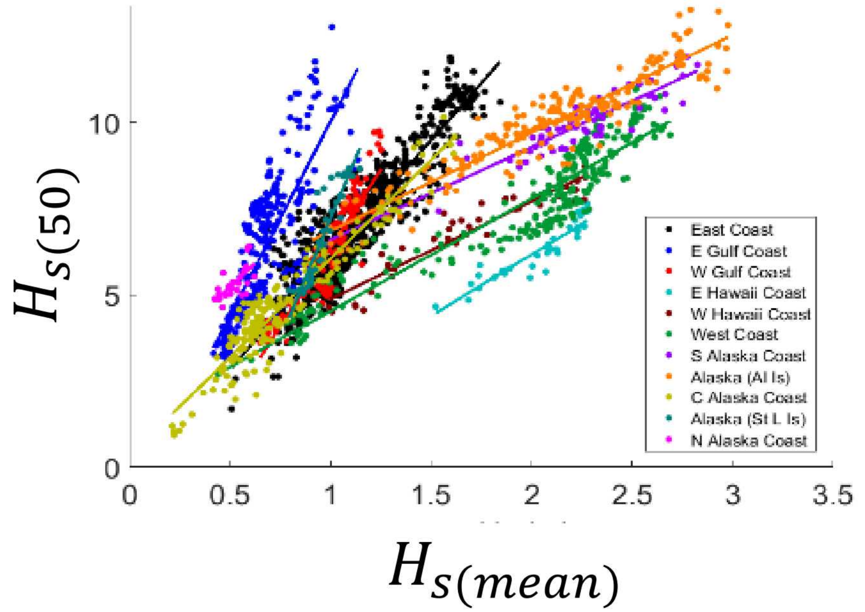
$$R = \frac{H_{s(50)}}{H_{s(mean)}}$$ [-]

- Characterizes risk relative to opportunity [Neary et al. 2017

Results: Additional metrics, extreme wave height, relative-risk ratio [Neary et al. 2019]

$H_{s(50)}$ $\quad$ $R = H_{s(50)}/H_{s(mean)}$





Regional correlations: extreme and mean wave heights [Neary et al. 2017]

Resource metrics: Temporal variability [Haas et al. 2019]

Temporal coefficient seasonal variability

$$t_s = \frac{J(max) - J(min)}{J_{avg}} \quad [\text{-}]$$

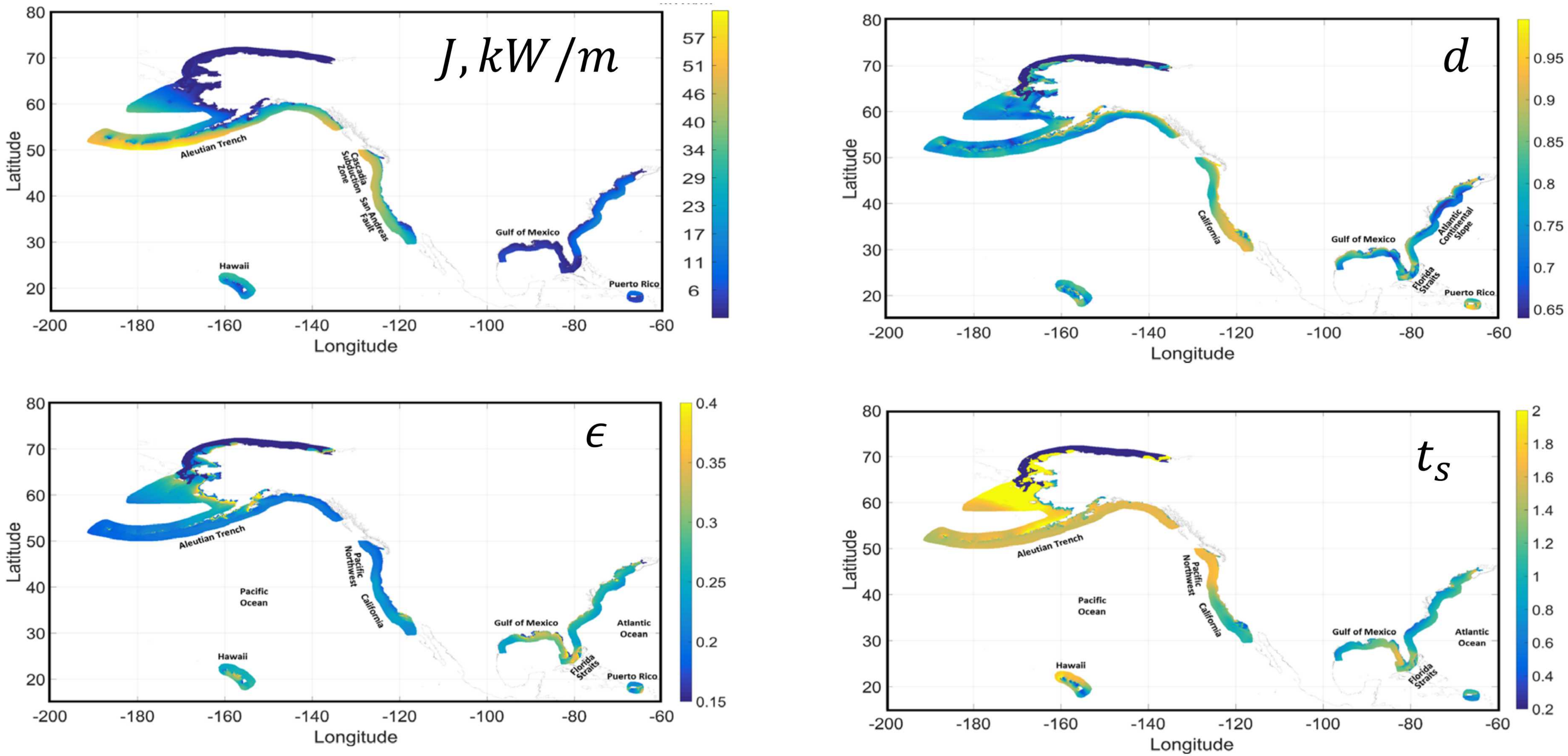
- Characterizes seasonal variability/constancy of resource

Temporal coefficient inter-annual variability

$$t_i = \frac{\sigma\left[AAE(Y) - (S_1 Y + S_2)\right]}{AAE} \times 100\ \%$$

- Characterizes inter-annual variability/constancy of resource

Results: Geographic distribution of resource metrics [Haas et al. 2019]



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