U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

NREL Transforming ENERGY

Opportunities and Challenges for Tidal, River, and Ocean Current Energy Technologies

ARPA-E Hydrokinetic Industry Day
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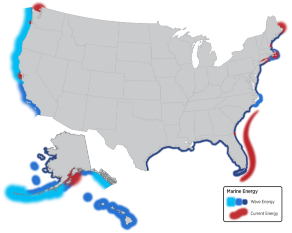
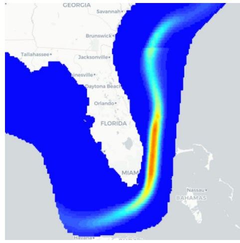
Overview



What is the resource?

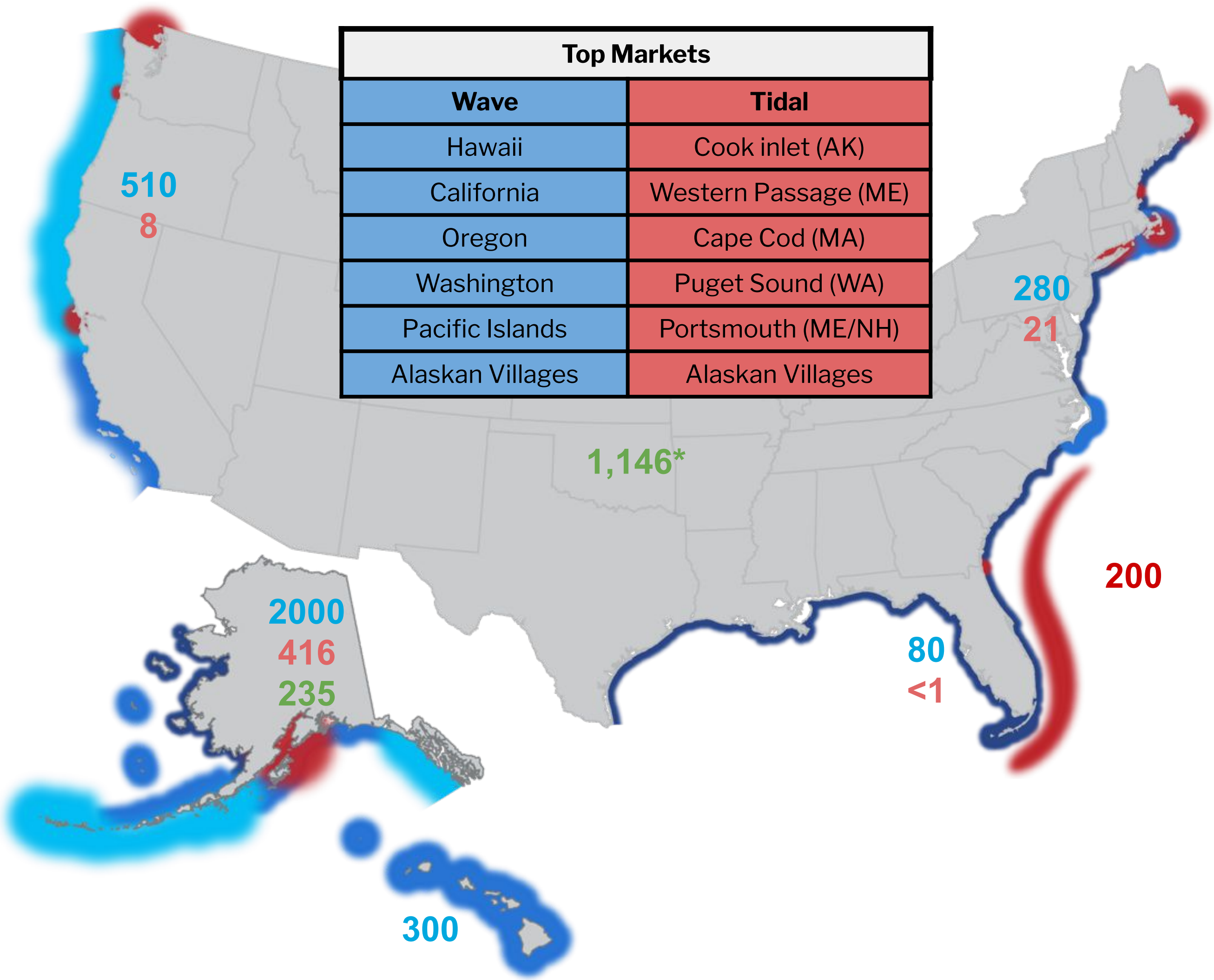
What are the technologies?



Utility scale opportunities

Blue economy opportunities

Tidal, river, and ocean current resources



Several tidal and ocean current utility scale resources with >100 MW of potential located near large coastal population centers

Significant portion of the resource is "stranded" in Alaska

Blue economy opportunities to provide power to microgrids (e.g. remote communities) and for off-grid scientific and industrial applications

	Resource (TWh/yr)	% US Generation
Ocean Wave	**3,170**	**78%**
Ocean Current	**200**	**5%**
Tidal Current	**445**	**11%**
River Current	**1,381**	**34%**

2018 US generation was 4171 TWh/year (476 GW avg)

Theoretical tidal energy resource - 445 TW-h/year

>93% of the US tidal resource is located in Alaska:

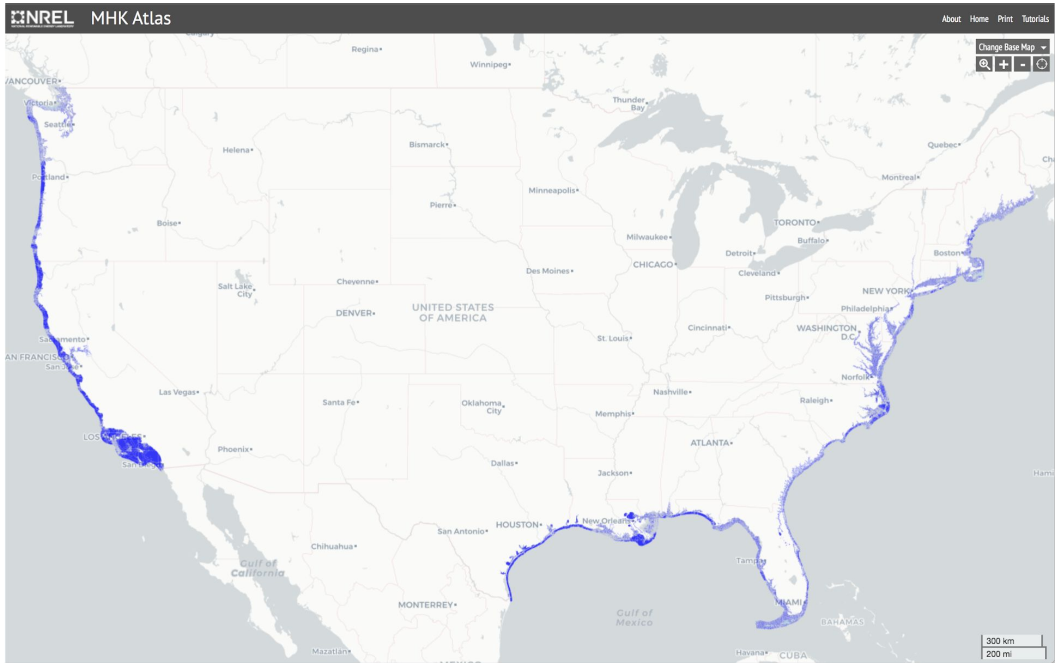
- AK resource ~2 orders-of-magnitude larger than electricity demand
- AK resource is far from load/grid → “Stranded” resource

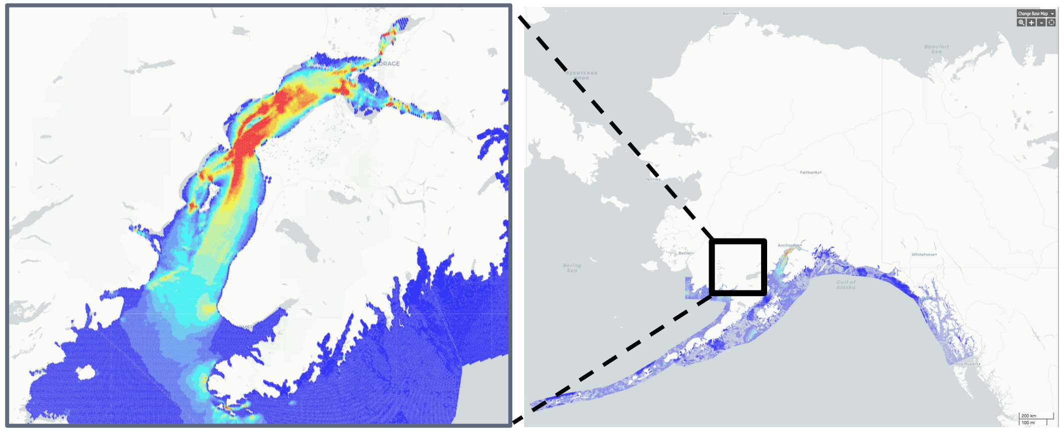
Maine and Washington both have >500 MW (>5.9 TW-hr/year) of theoretical resource

7 other coastal states each have >100 MW (>1.2 TW-h/year) of theoretical resource

State	Theoretical Resource (TW-hr/year)	Technical Resource (TW-hr/year)
ME	5.9	3.0
MA	0.6	0.3
RI	0.1	0.1
NY	2.5	1.2
NJ	1.7	0.8
DE	1.5	0.7
MD	0.3	0.2
VA	1.2	0.6
NC	0.5	0.3
SC	3.4	1.7
GA	1.9	1.0
FL	1.5	0.7
AL	0.1	0.0
LA	0.0	0.0
TX	0.1	0.0
CA	1.8	0.9
OR	0.4	0.2
WA	6.0	3.0
AK	415.8	207.9
East Coast	21.1	10.6
West Coast	8.2	4.1
L48	29.3	14.7
Total	445.2	222.6

2018 US generation was 4171 TWh/year





Theoretical river current resource - 1381 TW-h/year

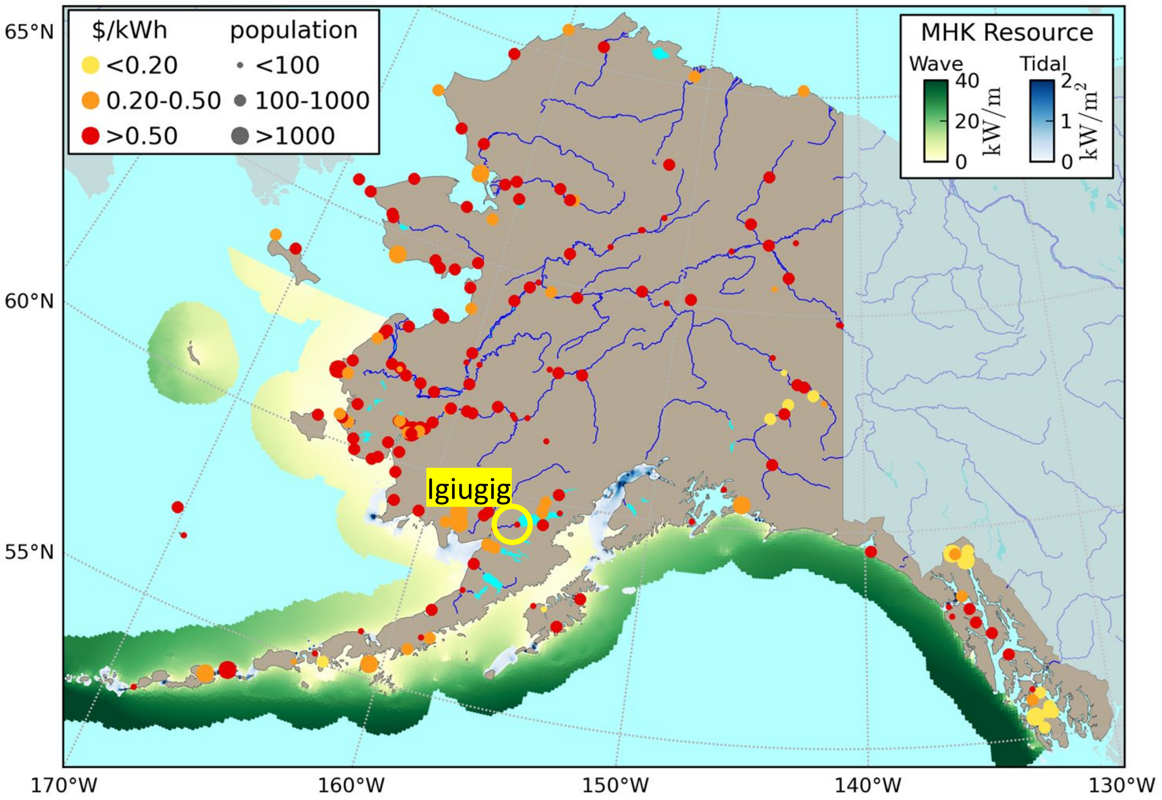
US resource concentrated in the Mississippi River, Pacific NW, and Alaska

Much of the resource in the Mississippi River, which has a relatively low flow velocity

Alaskan resource could provide power where grid connections are unavailable and power is expensive

Hydrologic Region	Theoretical Power (Annual Energy ,TWh/yr)	Technically Recoverable Power (Annual Energy, TWh/yr)
New England	14.4	0.2
Mid Atlantic	33.5	1.0
South Atlantic Gulf	38.5	1.2
Great Lakes	6.2	0.01
Ohio	79.2	6.9
Tennessee	20.4	1.0
Sauris Red-Rainy	1.8	0.03
Upper Mississippi	47.0	5.1
Lower Mississippi	208.8	57.4
Texas Gulf	8.9	0.05
Arkansas Red	45.1	1.3
Lower Missouri	79.8	5.6
Upper Missouri	74.3	2.8
Rio Grande	29.5	0.3
Lower Colorado	57.6	3.9
Upper Colorado	46.9	1.1
Great Basin	6.9	0
California	50.9	0.7
Pacific Northwest	296.7	11.0
Alaska	235	20.5
Total	**1,381**	**119.9**

US electricity in generation in 2018 was 4171 TWh/year



Marine energy provides many opportunities and benefits

Utility scale and off-grid opportunities
- Several grid scale opportunities
- sensors; AUVs / UUVs; algae; aquaculture
- Desalination
- Growth in developing maritime markets

Develop export markets
- Utility scale opportunities in Europe
- Worldwide market for off-grid power systems

Forecastable
- Tides and currents are predictable decades in advance
- Technologies can provide base load characteristics that other renewable sources lack

High power density
- Water currents are significantly more concentrated that wind and solar
- Smaller footprint than other renewable energy tech

Complements other renewables
- Seasonal variations
- Time of day variations
- Potential to offset a portion of grid storage

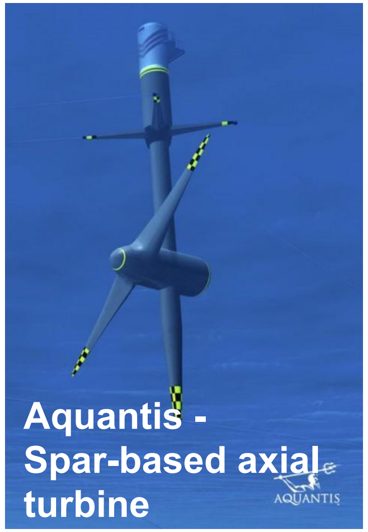
Expansive resource
- US Exclusive Economic Zone (EEZ) is 11.3M sq-km;
- US land area is 9.2M sq-km
- Technology requires minimal land use
- Opportunities for energy fishing

Limited surface expression
- Submerged energy capture out of the weather
- Minimize visual impact

Resilience
- Power source close to load
- Distributed power generation
- Potential for quick disaster response

Limited technology convergence in the industry


ORPC - Bottom-fixed and floating crossflow turbine


Aquantis - Spar-based axial turbine


Fumill - Archimedes screw


Atlantis - Bottom fixed axial turbine


Verdant Power - Bottom-fixed axial turbine

Minesto - Kite-based axial turbine


Scotrenewables - Floating axial turbine


SeaGen - Bottom fixed axial turbine

U.S. utility scale opportunity: Cook Inlet, AK

~35% of U.S. tidal resource - significantly larger than Alaskan electricity demand

5 km from a grid substation

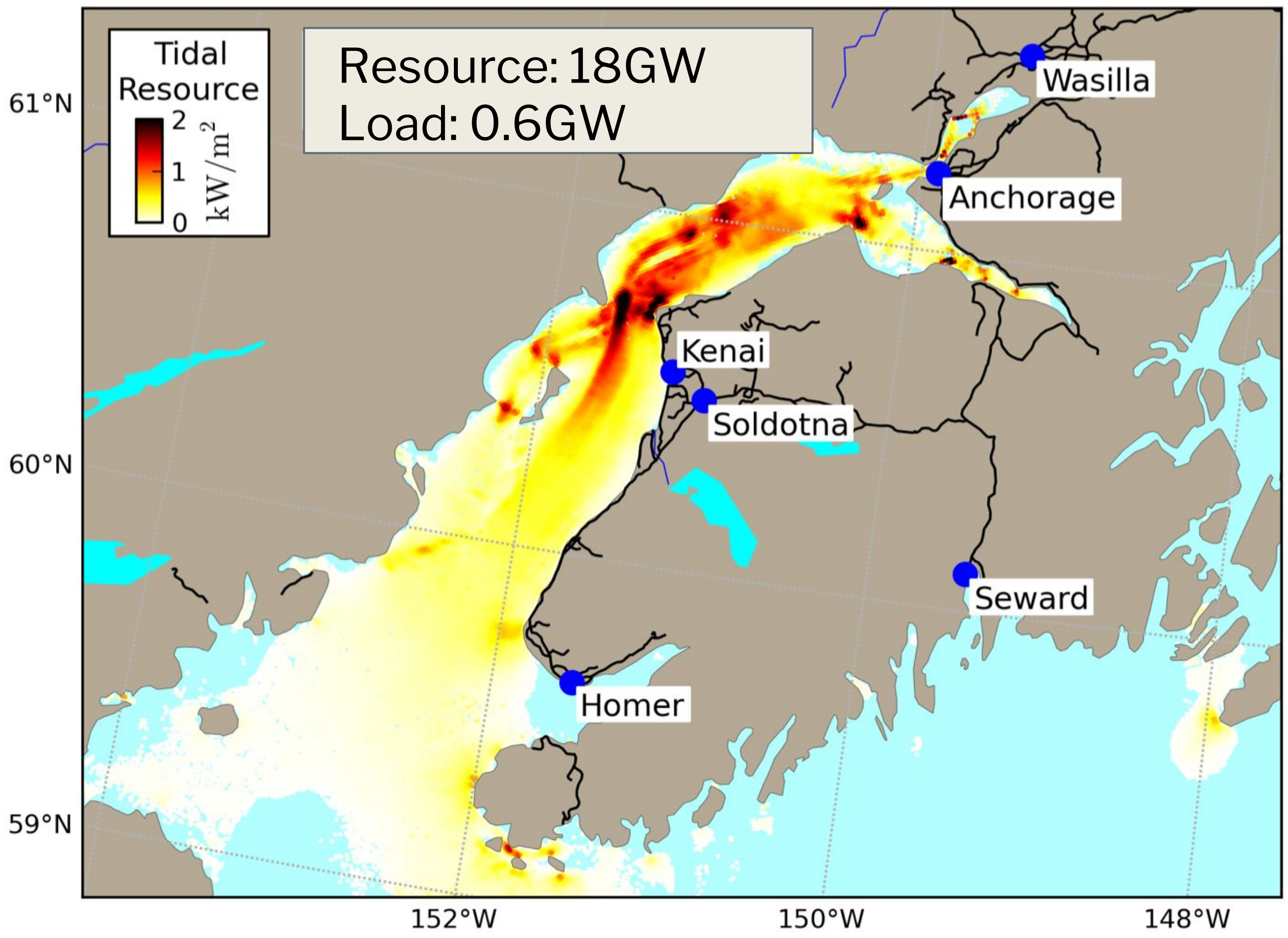
Retail electricity price of 0.20-0.25 $/kWh

120 MW of dispatchable hydro, 93 MWh Battery

Ongoing resource measurement campaign (2020)

Challenges:

- Balkanized utilities
- Submerged ice



Utility scale opportunity: Florida Current

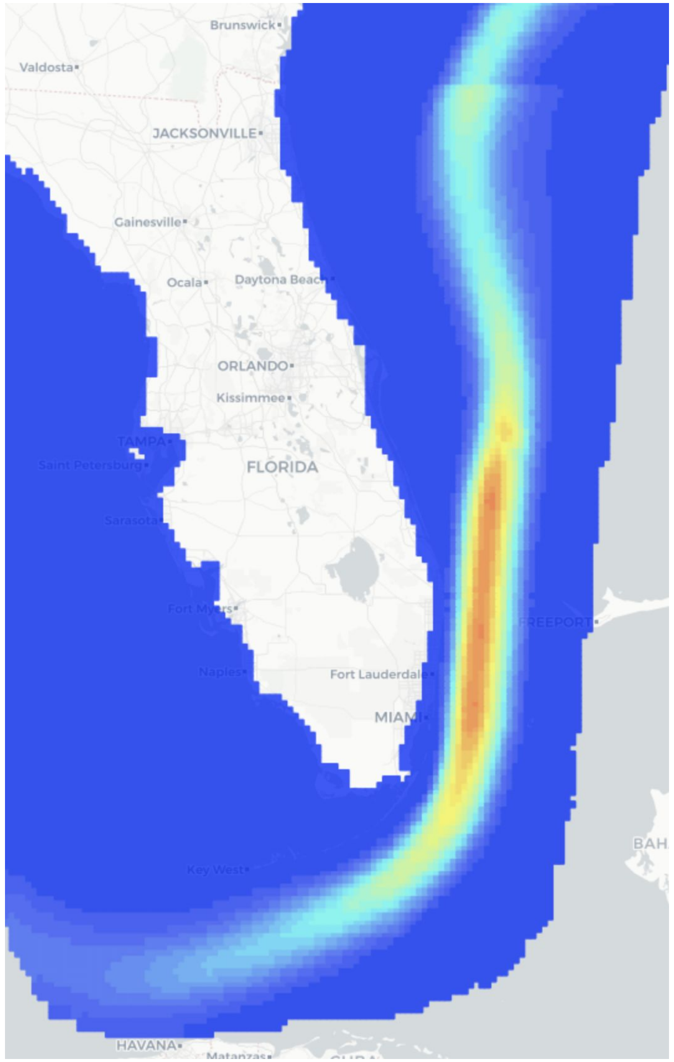
Florida current theoretical resource is ~20 GW (200 TW-h/year)

Ocean current turbines can produce baseload power → 2-4x higher capacity factor compared to other renewables

Little diurnal and seasonal variation compared to solar and wind

Technologies developed for Florida current could be exported and deployed globally

Challenge - Located 12-20 miles offshore in 250-450 meters of water



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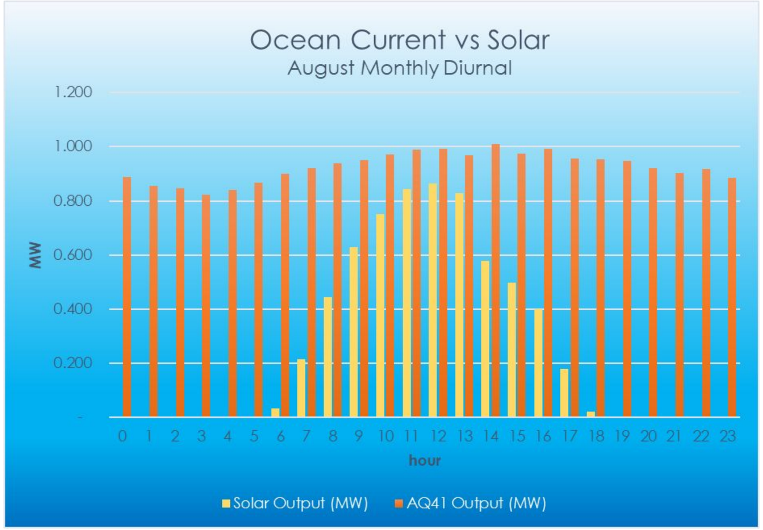


The **Blue Economy** is “the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems." (The World Bank, 2017)

The OECD predicts the "Blue Economy" will grow from $1.5 trillion in 2016 to $3 trillion by 2030

"In addition to generating electricity for use on-shore, power generated at sea could serve the needs of other existing or emerging ocean industries (e.g. aquaculture, oceanographic research, or military missions) [1]."

The Blue Economy is recognized by the OECD [2], NOAA [3], The Economist [4], and the World Bank [5] as a market that is likely to grow rapidly over the coming decades

[1] Science and Technology for America's Ocean: A Decadal Vision
[2] The Ocean Economy in 2030, Organisation for Economic Cooperation and Development, 2016
[3] The Ocean Enterprize, NOAA, 2016
[4] The Potential of the Blue Economy, The World Bank, 2017
[5] The Blue Economy, The Economist, 2015

DOE launched the Powering the Blue Economy (PBE) initiative to support the development of marine energy technologies for the blue economy

Technology attributes of marine energy beneficial to many blue economy markets:

- Provide both electrical and mechanical power
- Minimal surface expression improving storm survivability
- Opportunities for co-design and integration with other infrastructure and systems
-

A new strategic focus for DOE. Goals include:

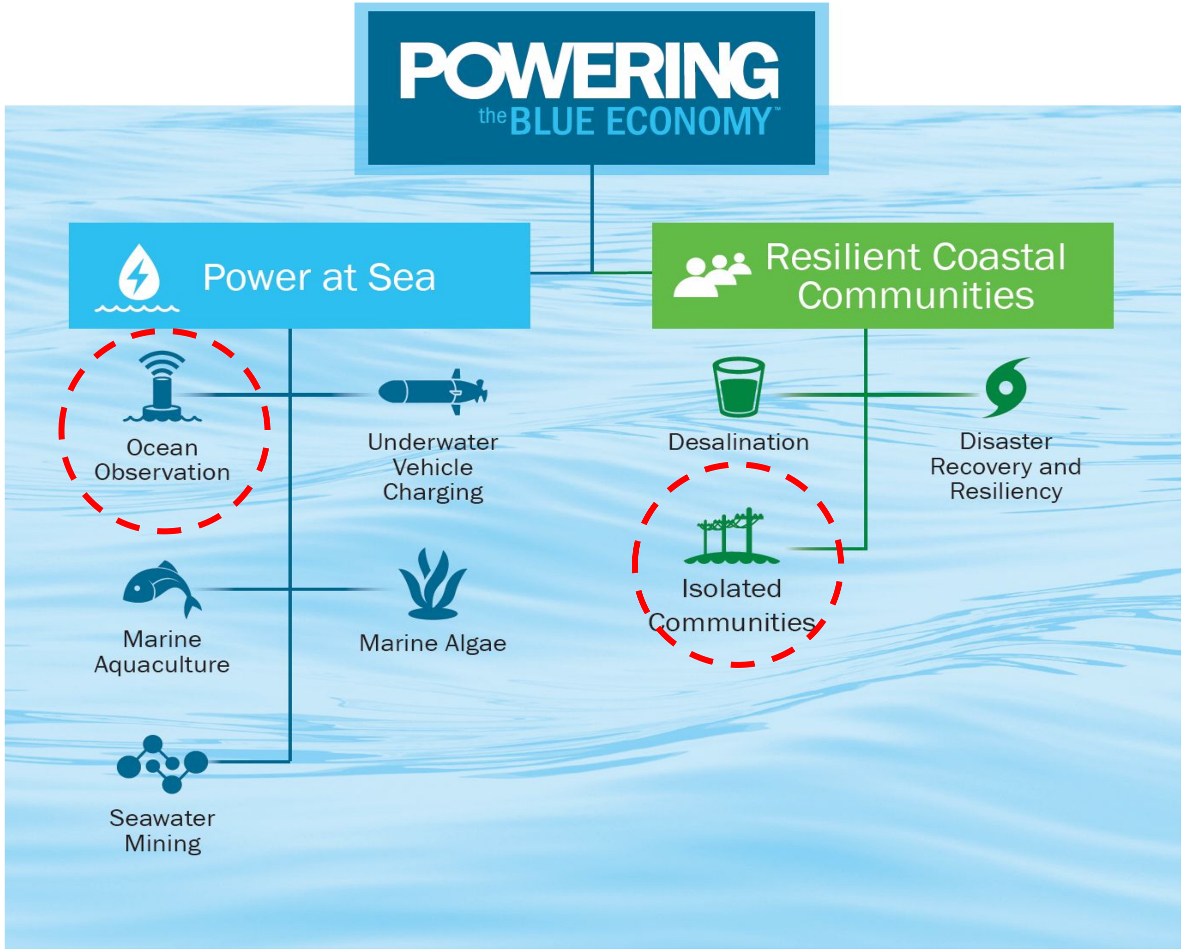
- Understand the power and technology requirement of blue economy markets
- Advance technologies that can provide power for PBE applications

Reference: energy.gov/eere/water/downloads/powering-blue-economy-report

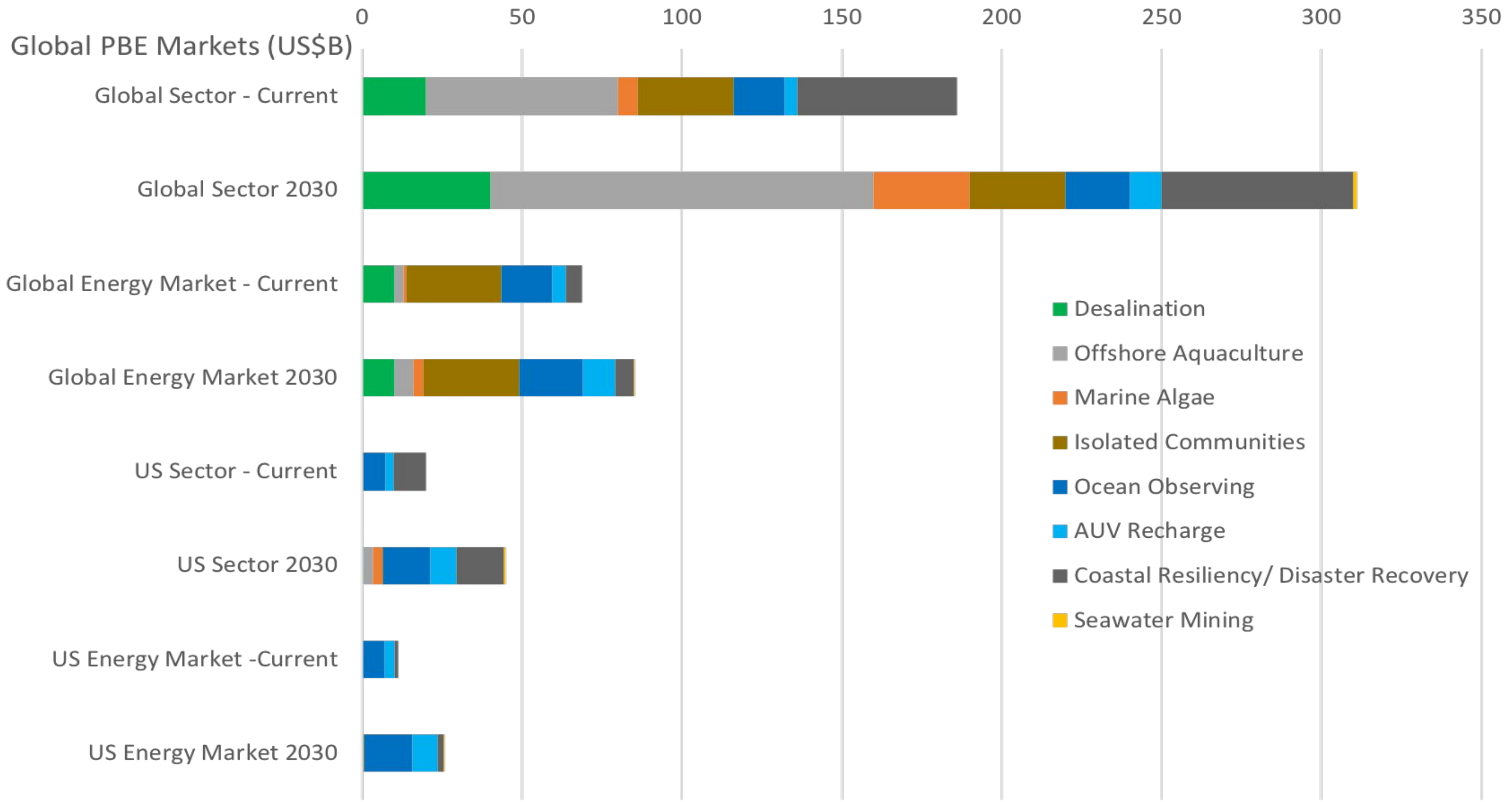
“Power at Sea” and “Resilient Coastal Communities” were identified as market sectors where marine energy can provide value

Blue economy markets offer viable and valuable end points for marine energy technology developers, as well as a pathway that supports the development utility scale technologies

These markets provide opportunity to for economic growth in the US and internationally



Global PBE sector is expected to expand to over $300 B by 2030



Estimates based on 3rd-party market studies and best understanding of energy costs as fraction of total market size. Study did not quantify other potential PBE sectors (e.g., transportation, electrolysis)

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PBE opportunity: Powering isolated communities

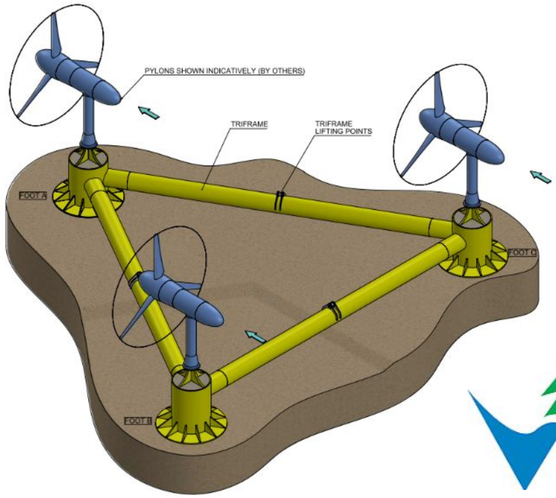
- FERC license issued to the Igiugig Village Council for a two-device river turbine power system
- 35 kW ORPC RivGen® 2.0 deployed in August 2019
- Connected to diesel microgrid
- Installing Energy Storage on microgrid in 2020
- Operational following frazil ice occurrence in late December 2019/early January 2020
- Plan to operate during sockeye salmon smolt and adult migrations– May thru July 2020
- Complete power system (two devices, smart grid and energy storage) will allow for 100% renewable operations for Village

PBE opportunity: Powering isolated communities

PBE opportunity: Powering isolated communities

- Fifth generation (Gen5) KHPS with being deployed and tested at the RITE test site in the East River near New Your City
- TriFrame mounting system supports three Gen5 KHPS at once onto seabed cost-efficiently
- Benefits of the new mounting system:
  - Provides for village <u>and</u> utility-scale systems ranging from 100 kW to 1.5 MW or more on each TriFrame™
  - Allows design efficiency for village and utility-scale systems in specific sites and reaches of water
  - Lowers costs due to faster deployment and retrieval
  - Makes use of local marine engineering support and services; not requiring heavy lift vessels (HLV)

Gen5 KHPS TriFrame™ Mounting System/Module



VERDANT POWER

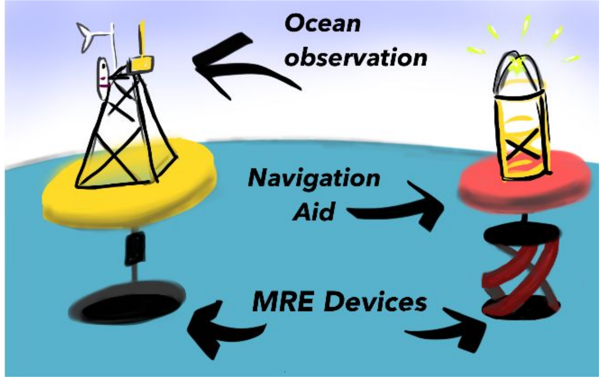
Power (kW) Generated by Various Rotor Sizes (m) and Water Current Speeds (m/s)

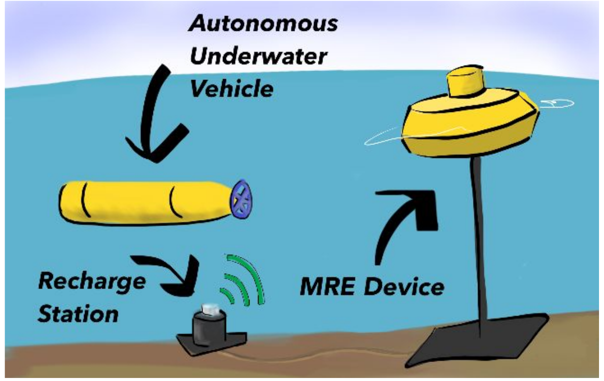
KHPS Turbine	Rotor size (m)	2 m/s (kW)	3 m/s (kW)	4 m/s (kW)
Gen5, 5m	5	28	95	224
	7	55	190	450
Gen5, 10m	10	115	385	920
	11	138	470	1,110

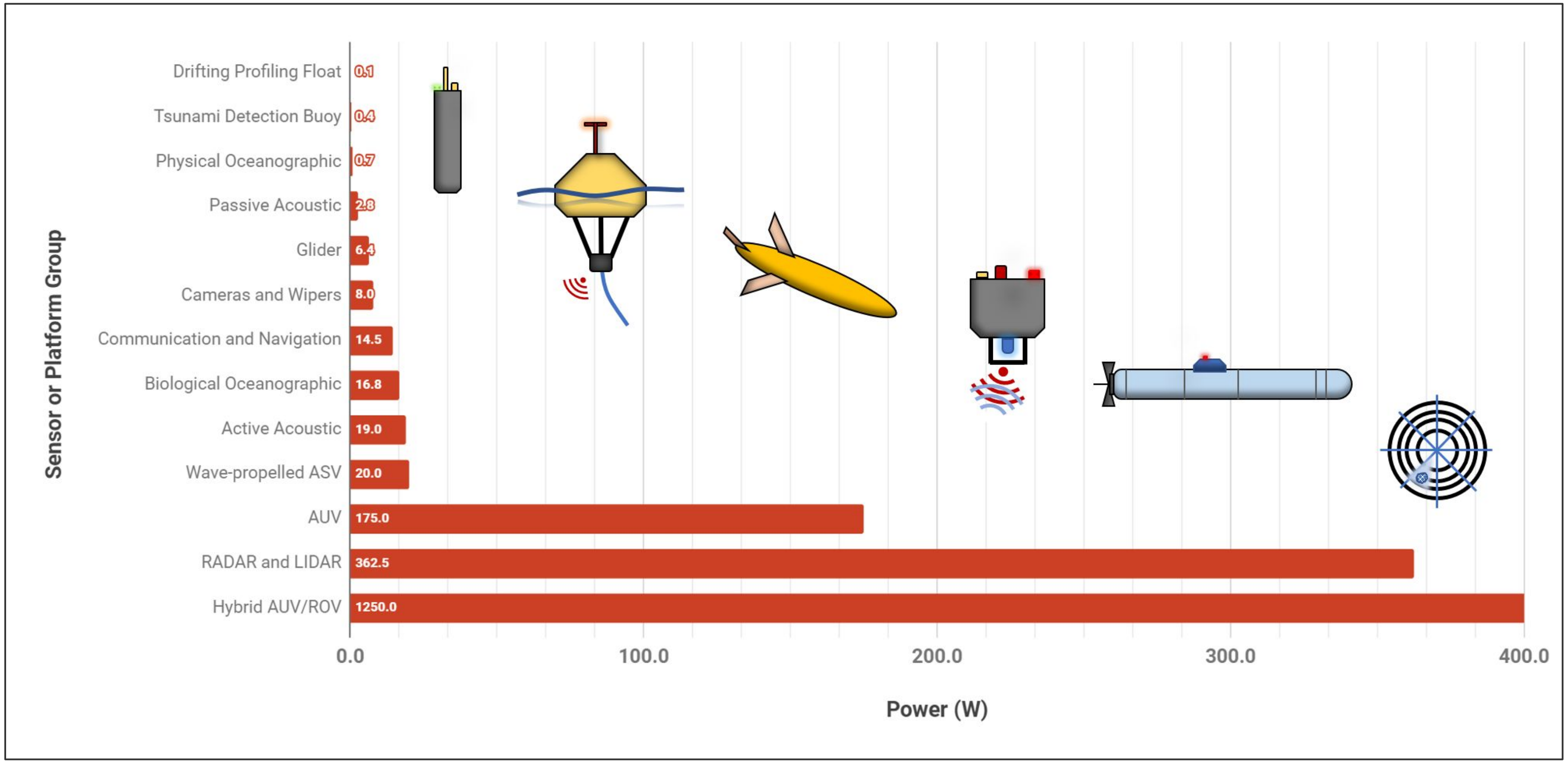
PBE opportunity: Powering ocean observing systems

NREL and PNNL performed extensive interviews to determine the power needs of ocean observing systems

Results: Significant opportunities for coupling marine energy systems capable of producing <1 kW







Reference: R. Green, et al., Enabling Power at Sea, Oceans 2019
osti.gov/biblio/1573195-enabling-power-sea-opportunities-expanded-ocean-observations-through-marine-renewable-energy-integration-preprint

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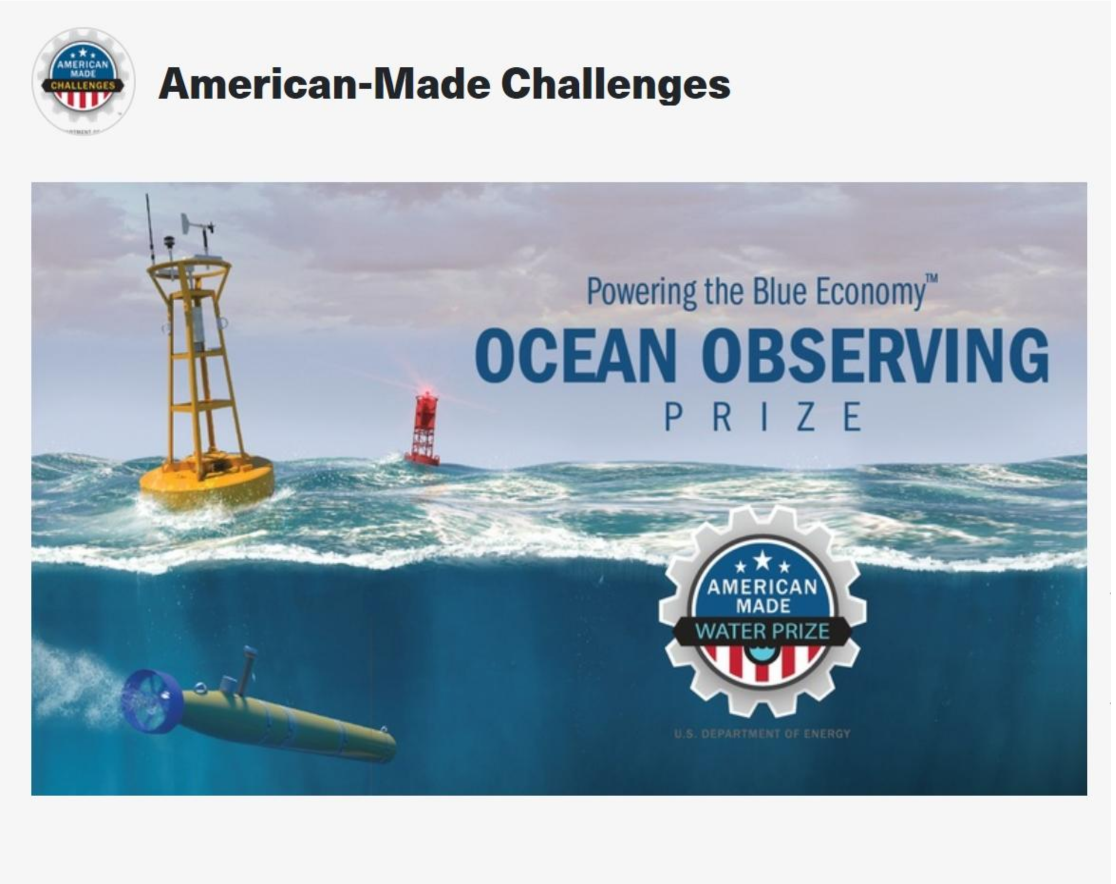
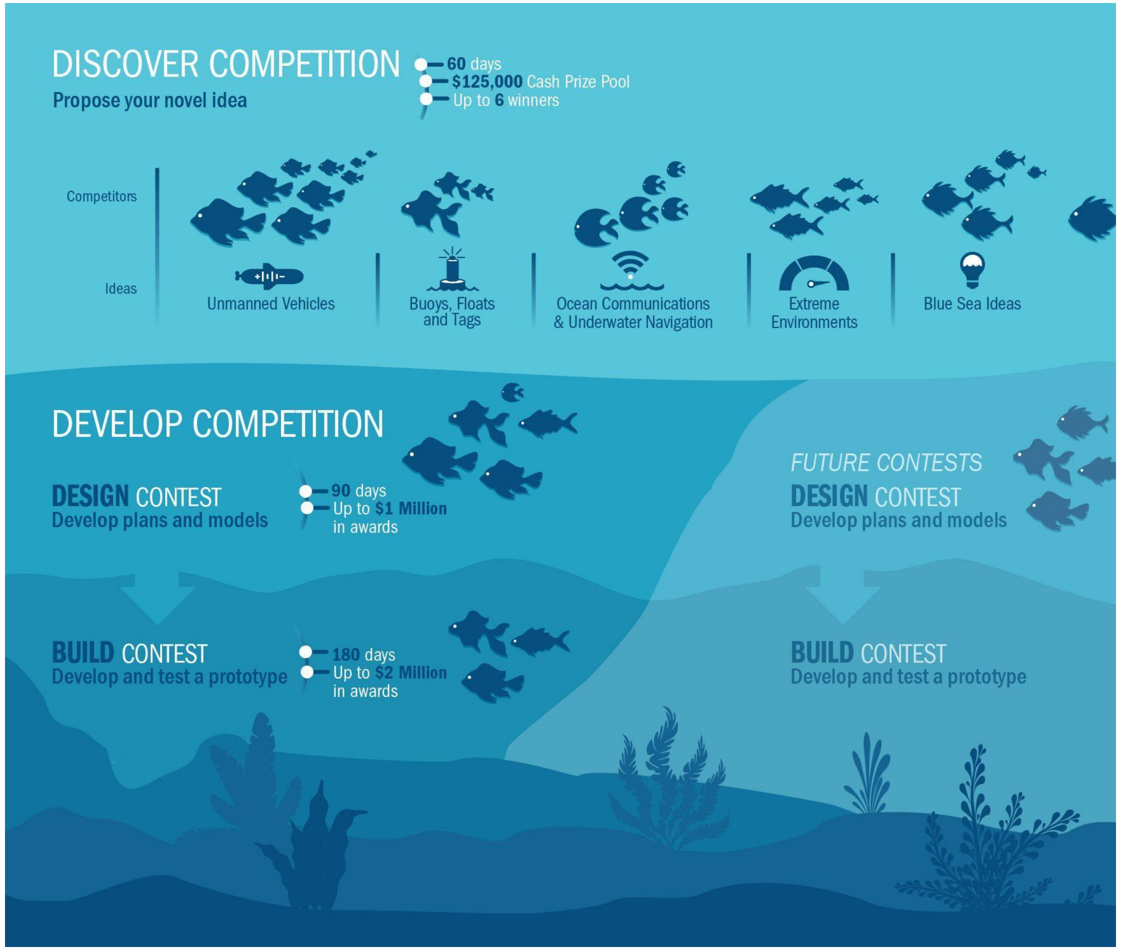
PBE opportunity: Powering ocean observing systems



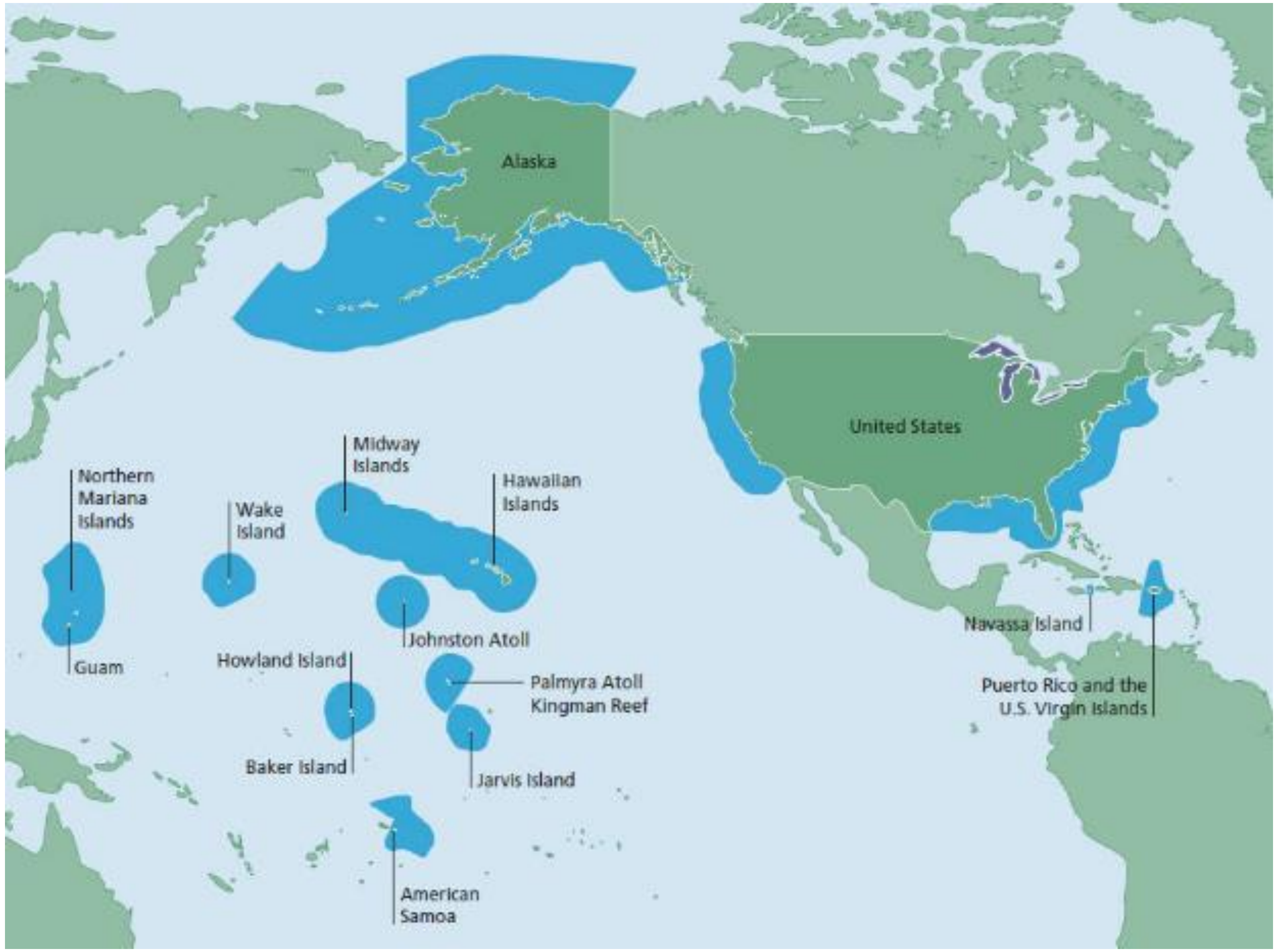
https://www.herox.com/oceanobserving



PBE opportunity: Access "stranded" marine energy resources

U.S. Exclusive Economic Zone (EEZ) is approximately equivalent to the total U.S. land area

There is a large marine energy resource located far from load centers

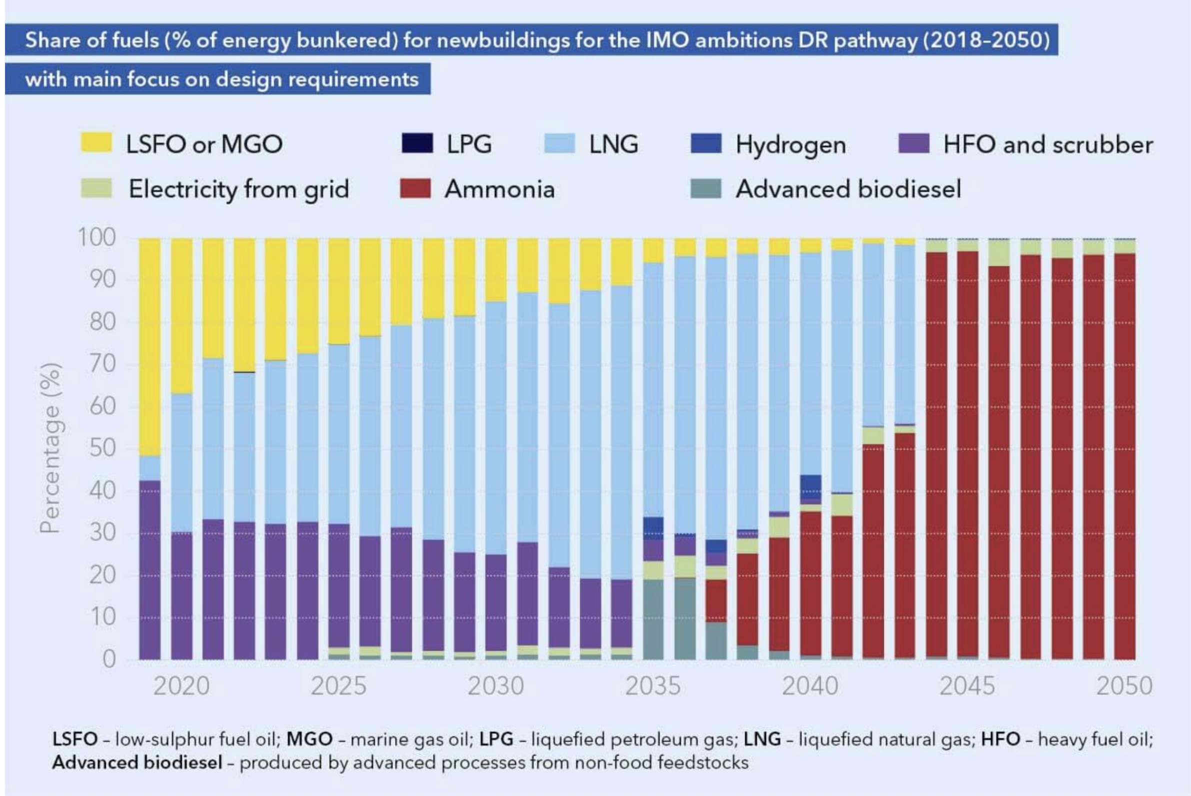


PBE opportunity: Access “stranded” marine energy resources

Potential for renewable fuel production

- Hydrogen, ammonia or methanol can be remotely produced and used where it is needed
- E.g. shipping industry uses over 2900 TW-h/year (~75% of U.S. electricity generation) of energy and projections suggest a move towards alternate fuels → marine energy could support fuel generation in remote locations
- Opportunities for energy fishing

Forecasting the effects of world fleet decarbonization options



Source: dnvgl.com/expert-story/maritime-impact/Forecasting-the-effects-of-world-fleet-decarbonization-options.html -

What are the challenges faced by the current energy industry

ARPA-E and Water Power Program collaboration opportunities
- Open water testing / TEAMER test facilities
- Utility scale and blue economy technology development
- Design tool development / Co-design projects

System design and optimization (co-design)
- Maximize energy capture while controlling loads
- Reduce cut-in speed / capture low energy density resource
- Minimize operational and extreme loads
- Reduce material costs
- Enable efficient IO&M
- Optimal design of floating and flying systems
- Array optimization
- Few design tools specifically for current turbines, particularly crossflow
- Co-design tools to improve integrated system performance
- Development of innovative current energy concepts

Blue economy
- Hybrid energy system design and control
- Underwater charging
- Non-tethered station keeping
- Novel (e.g. non-rotor) turbine designs and materials
- System integration/co-design with alternate end use systems (e.g. desalination and, ammonia, hydrogen, and methanol production)
- Robust and reliable systems for remote deployments
- Applicability to low-resource sites

Simulation tools
- Development of design tools from low-fidelity to high-fidelity
- Control system design - particularly for floating and tethered systems

Grid integration
- Technologies and methods that enable cost effective grid integration (e.g., low cost cable systems)
- Microgrid design, controls, and system integration for current energy systems
- Aggregation of outputs from multiple units for transmission to shore

Materials and components
- Optimized designs for moorings, electrical cable systems, and grid interconnections
- Deployment and retrieval innovations (e.g. self deploy and retrieval for remote systems)
- High torque / low speed generators
- New blade materials
- Blade designs to sustain high hydrodynamic loading and the saltwater environment
- Biofouling of critical components
- Accelerated life testing of materials and components in salt

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Thank you!