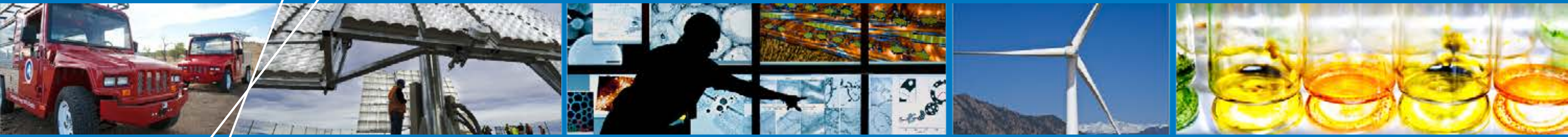
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

BOEM Offshore Renewable Energy Workshops:

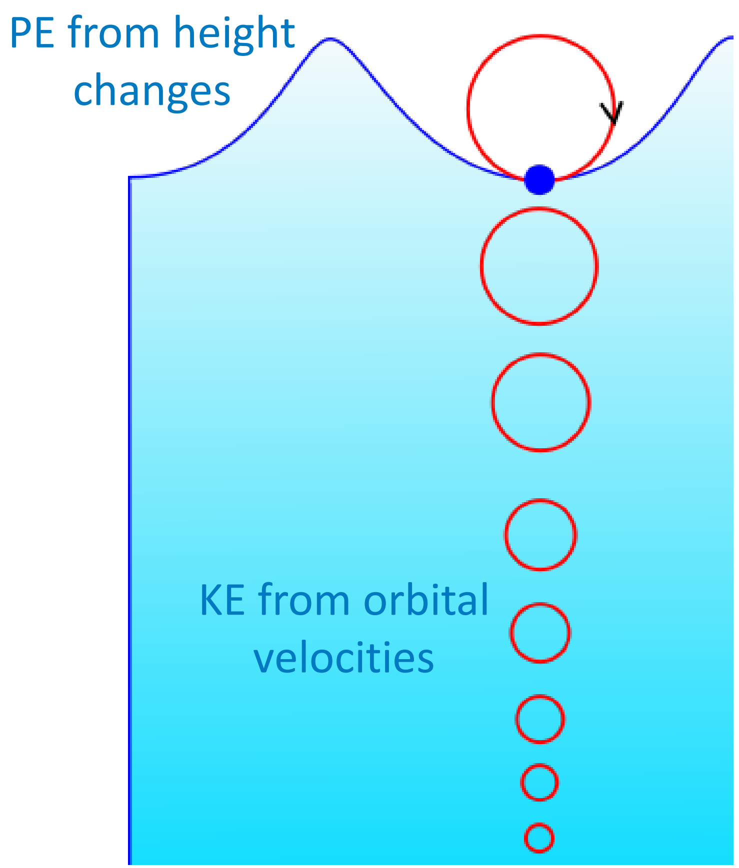
Ocean Wave Energy Technology



Dr. Robert Thresher
NREL Research Fellow

Sacramento, California
July 30, 2014

Wave energy the kinetic + potential energy in a wave



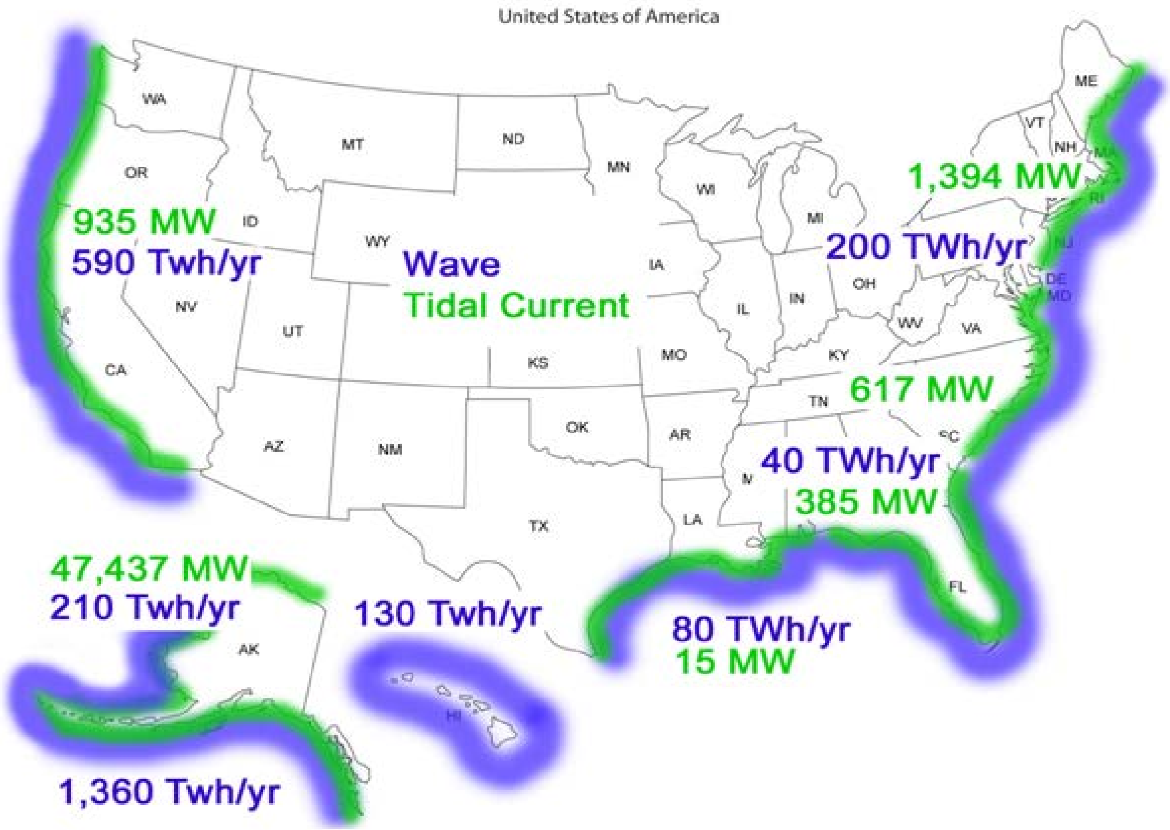
Relevant wave properties (e.g. velocity, pressures, etc.) can be derived using Stokes wave theory

The wave power per unit wave crest in deep water is:

$$P = \frac{\rho g^2}{64} H^2 T \; [\frac{W}{m}]$$

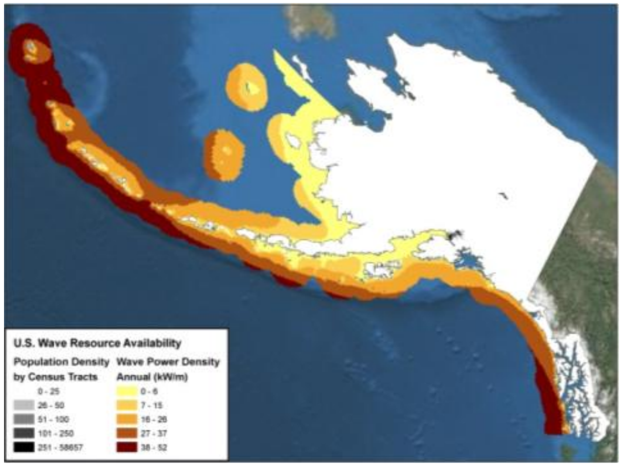
The U.S. Theoretical Wave & Tidal Resource

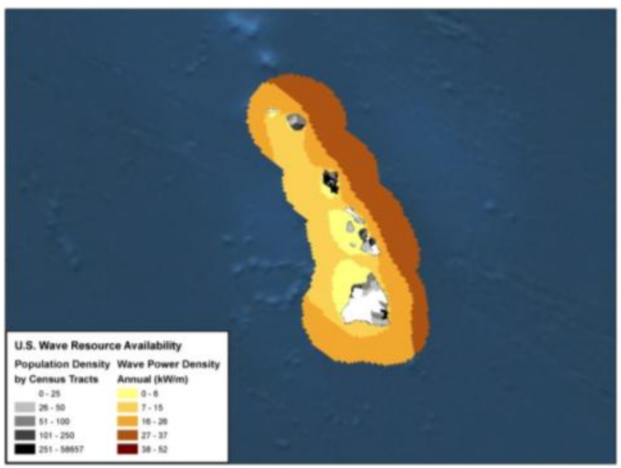
U.S. Electricity Usage:
- Consumption = 3886.4 TWh/yr
- Generating Capacity = 1000 GW

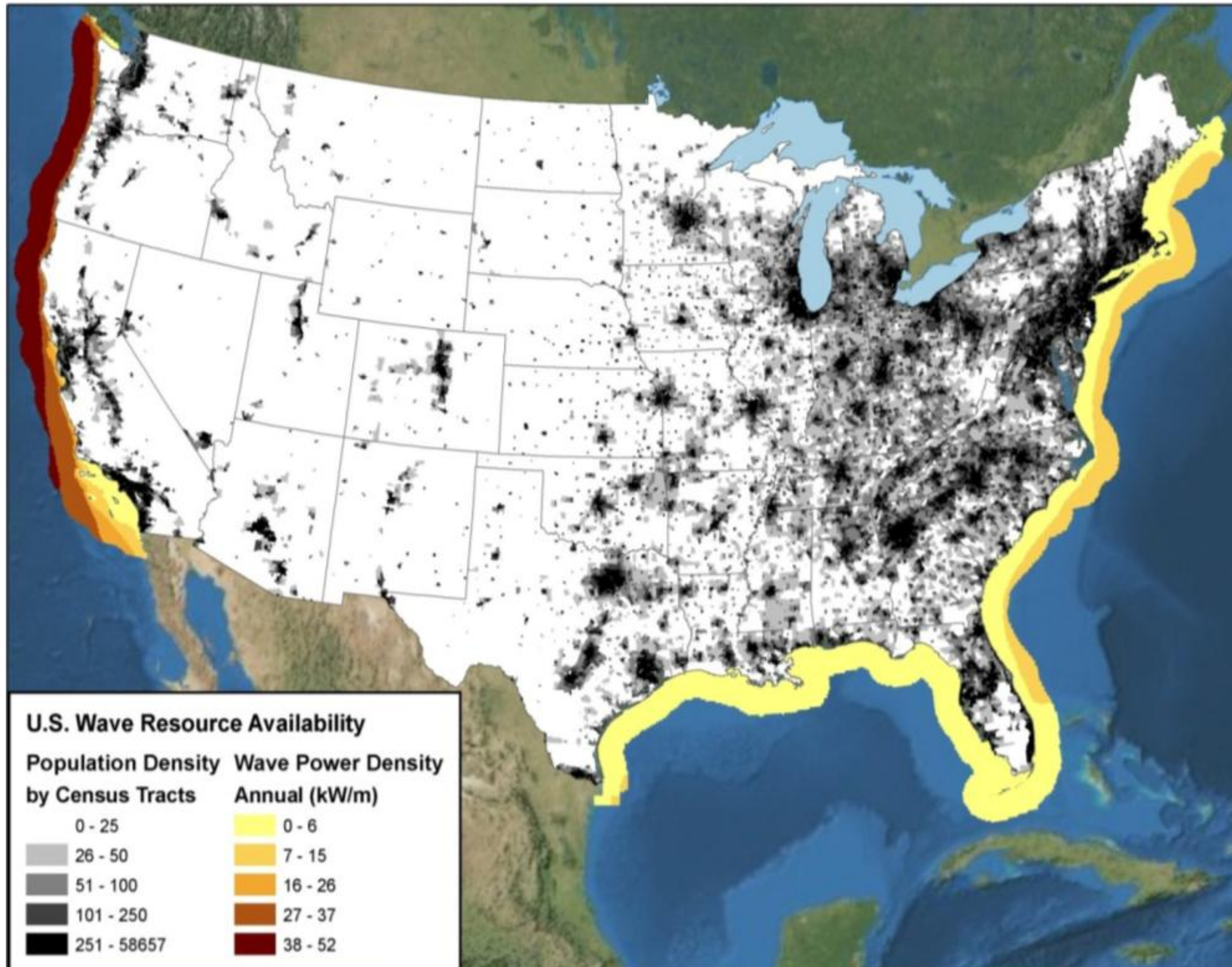


Resource Estimate References:
- Wave Energy: http://maps.nrel.gov/node/45/launch
- Tidal Currents: http://www.tidalstreampower.gatech.edu

Wave Energy Resource Maps

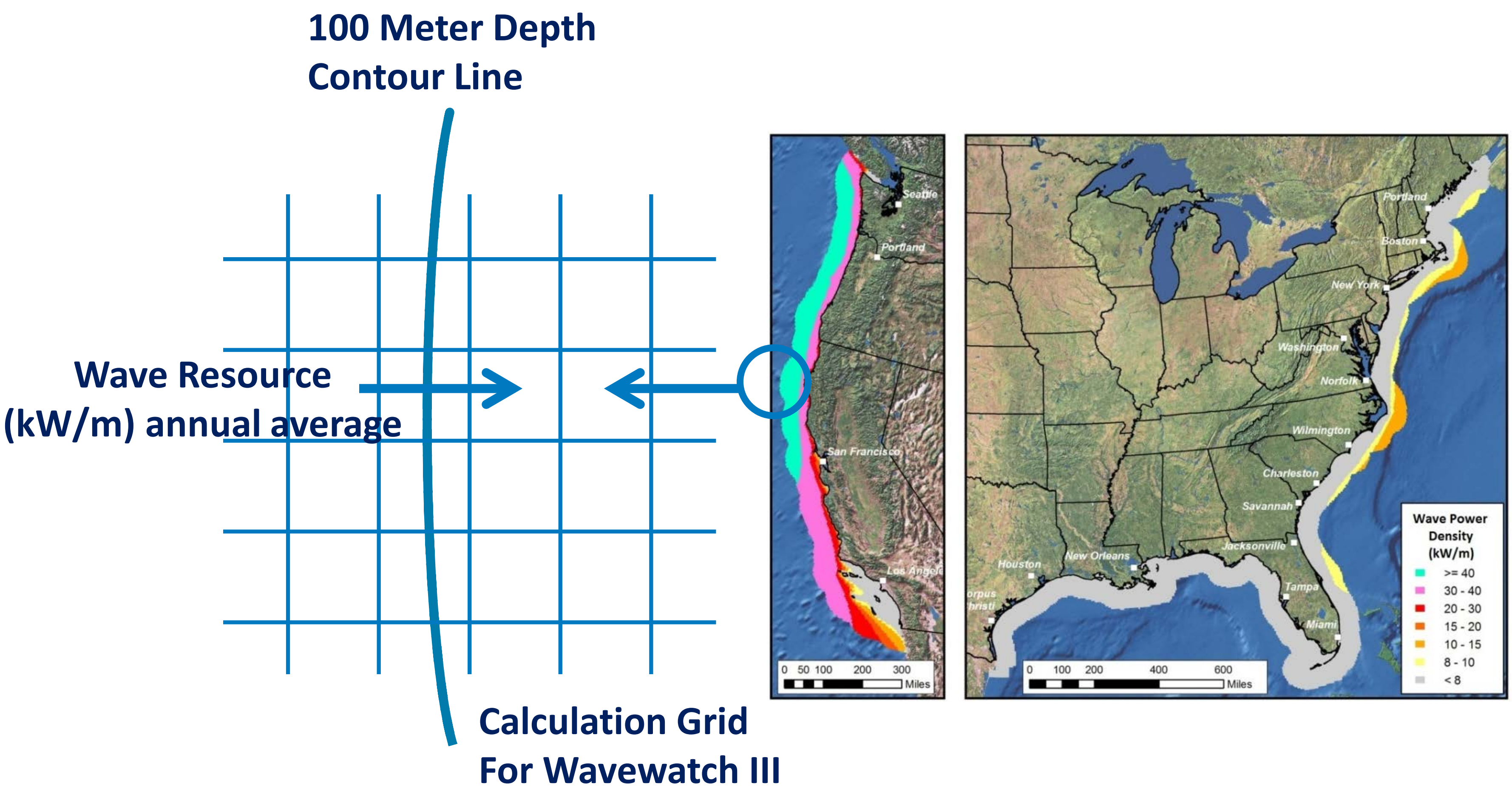




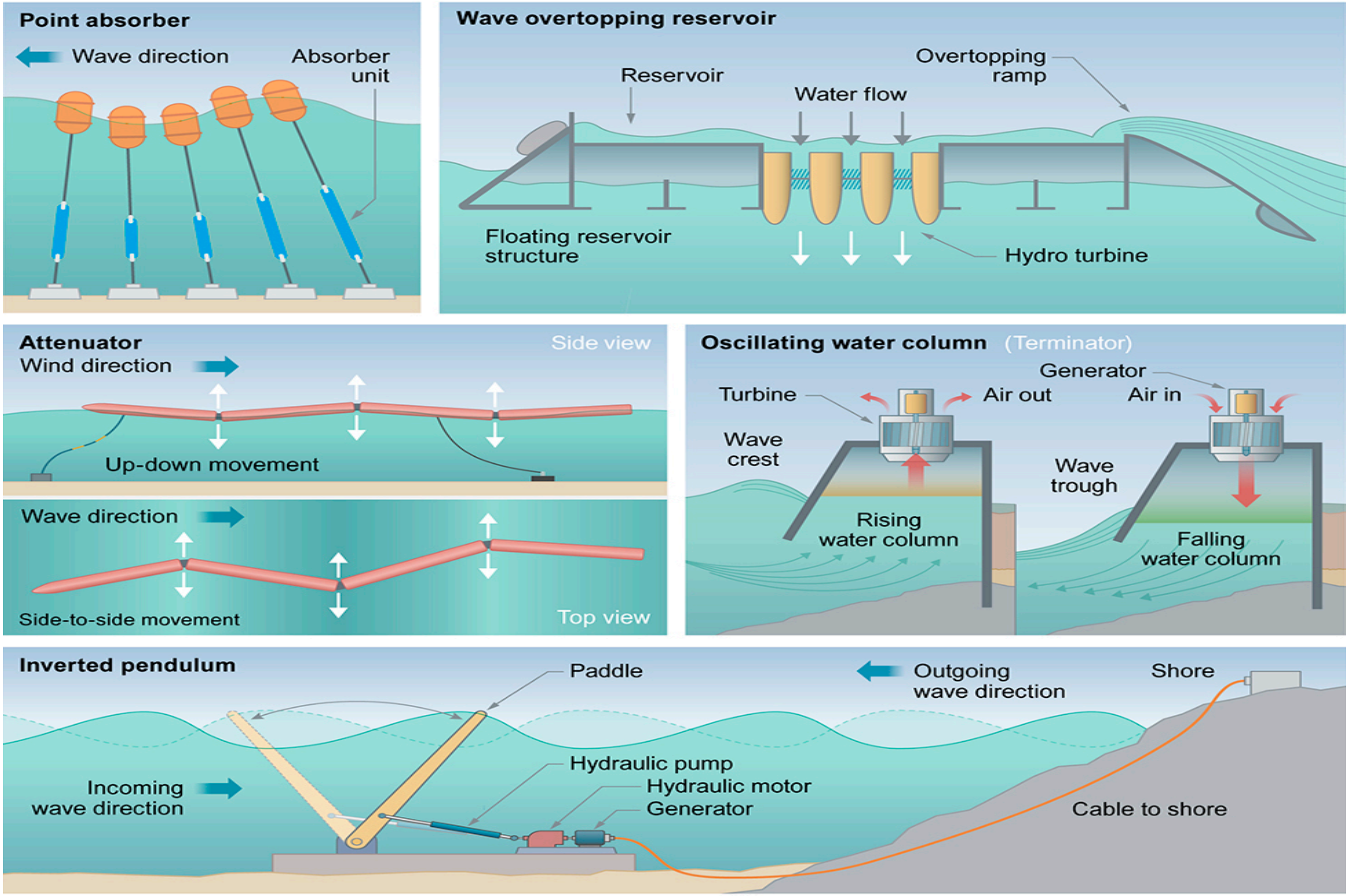


http://maps.nrel.gov/re_atlas

Method For Estimating the U.S. Wave Resource



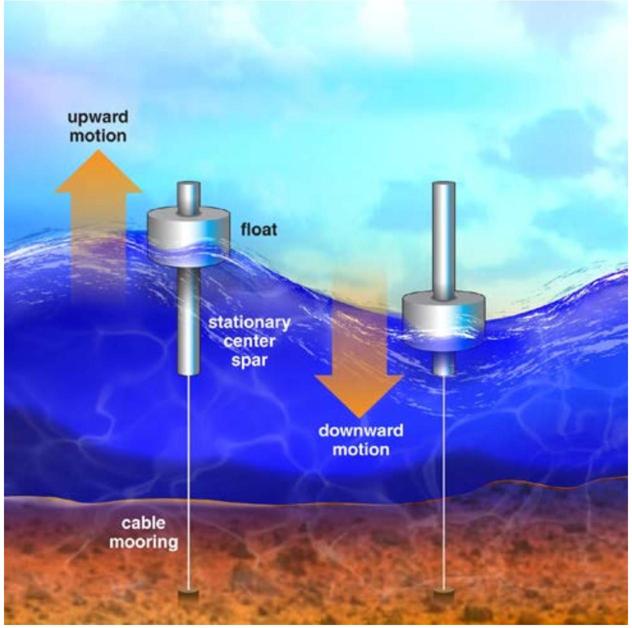
The Many Wave Energy Technologies



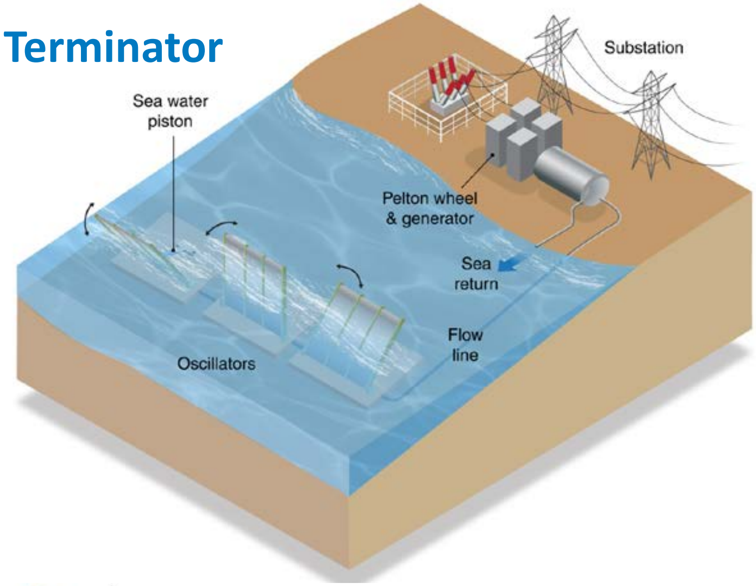
Source: Renewable Energy Futures Study NREL TP-6A20-52409-2

How do Wave Energy Converters Function?

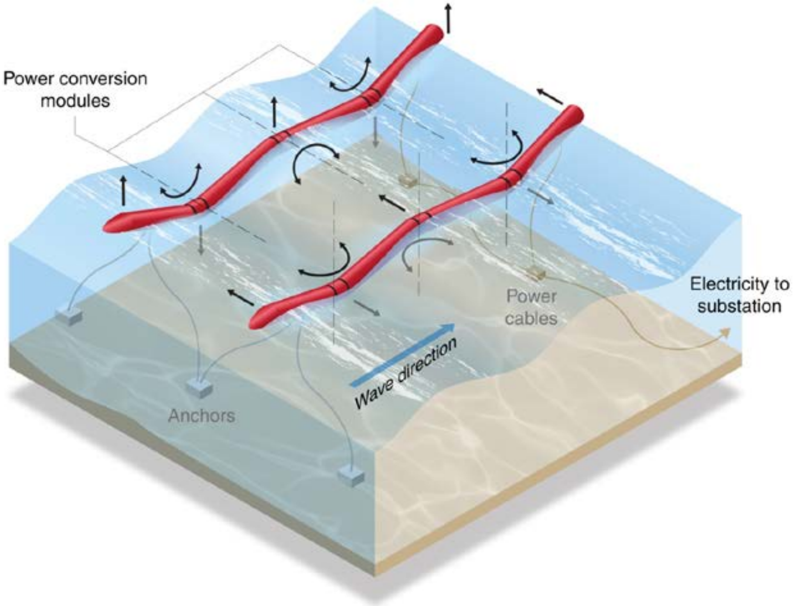
Point absorber



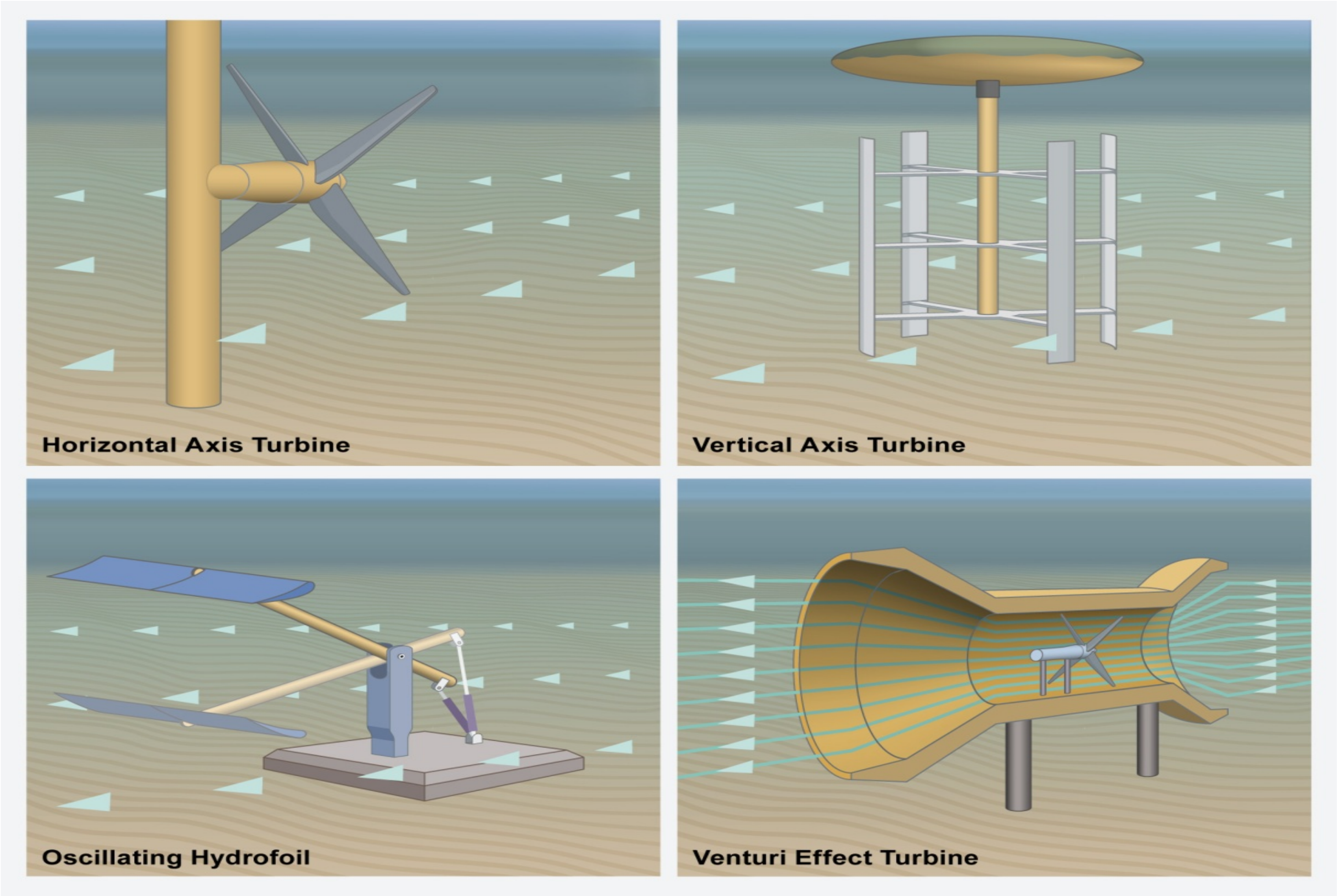
Terminator



Attenuator



The Several Tidal, River and Ocean Current Technologies

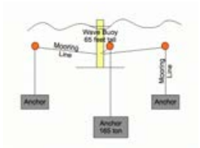


Source: Renewable Energy Futures Study NREL TP-6A20-52409-2

DOE is Using Technology Readiness Levels

Technology Readiness Levels:
A Disciplined Protocol for Technology Development

DOE TRL 1-3
Discovery / Concept Definition / Early Stage Development, Design and Engineering



DOE TRL 4:
Proof of Concept

DOE TRL 5/6:
System Integration and Laboratory Demonstration

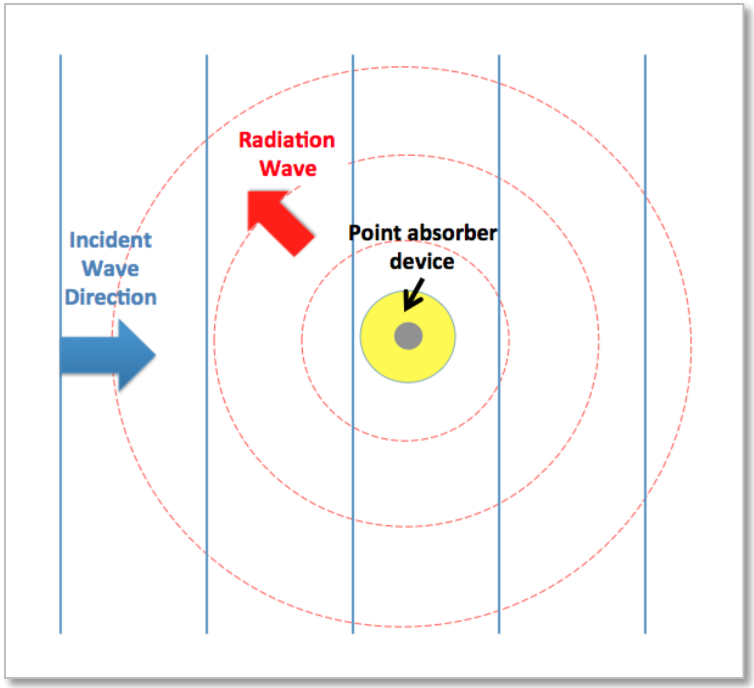
DOE TRL 7/8:
Open Water System Testing, Demonstration, and Operation

DOE TRL 9:
Array Testing

DOE TRL 10:
Commercialization

Modeling Wave Energy Capture

Point absorber interacting with waves



A prototypical TRL-7/8 point absorber
OPT's PowerBuoy Wave Energy Converter
http://www.oceanpowertechnologies.com/

(NREL PIX # 17114)

Reduced order (linear) model for operation

The equation of motion for a single body wave converter is:

Determined using potential flow frequency domain analysis

$$(M + m_A)\ddot{X} = F_{EX} - F_{RD} + F_{HS} + F_V + F_{PTO}$$

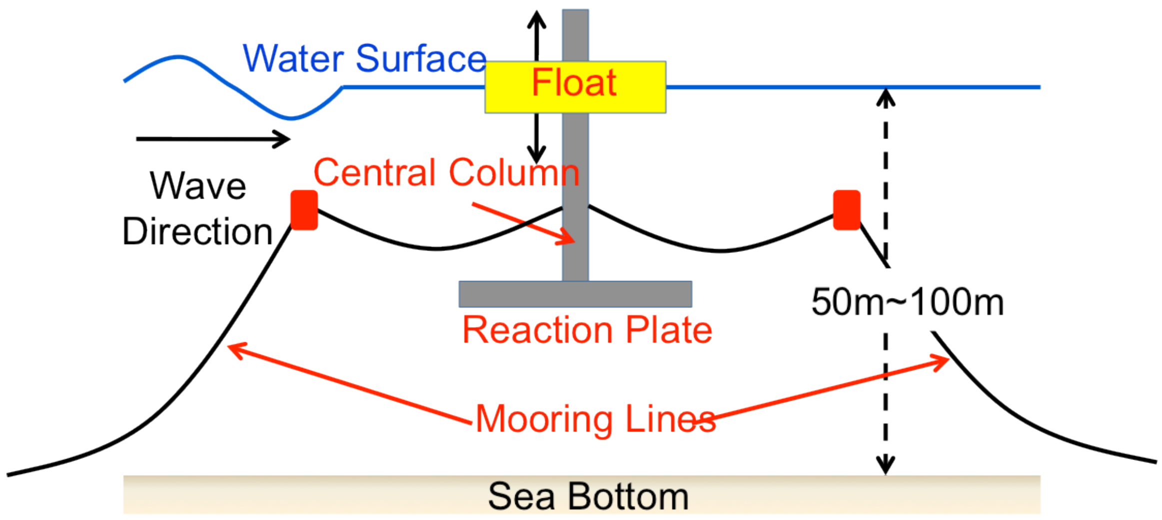
- $(M + m_A)$: Body Mass & Added Mass Coefficient
- $\ddot{X}$: Acceleration
- F_{EX}: Wave Excitation Force
- F_{RD}: Radiation Damping Force
- F_{HS}: Hydrostatic Force
- F_V: Viscous Force
- F_{PTO}: PTO Force

Key assumptions:

- **Small amplitude motion**
- **Linear waves only**
- **No overtopping or slamming**

Multi-body wave converters will have an equation for each body with constraint equations

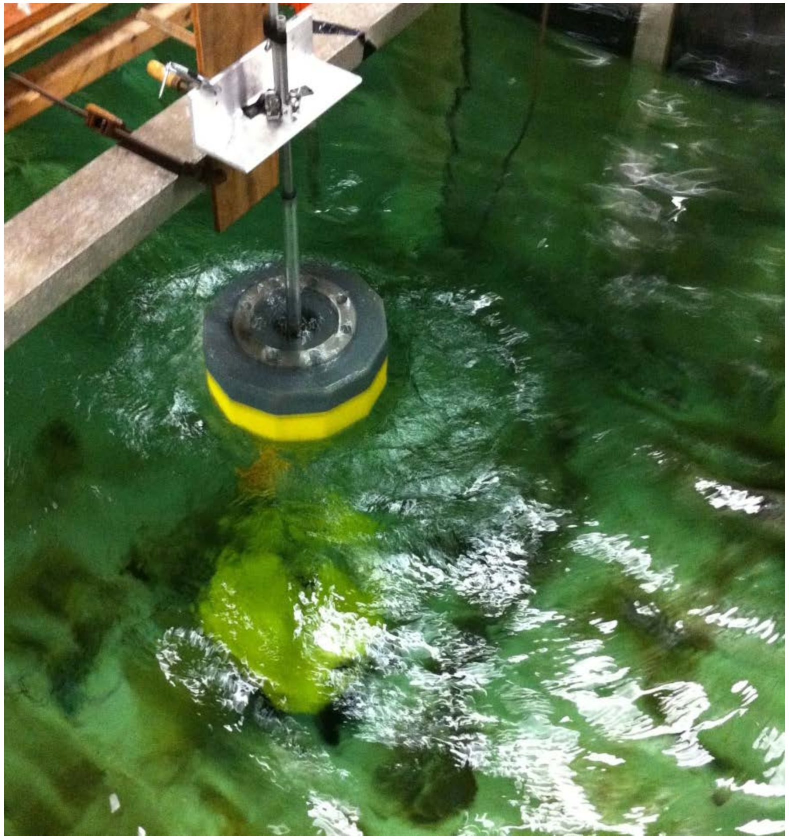
Example Floating Point Absorber



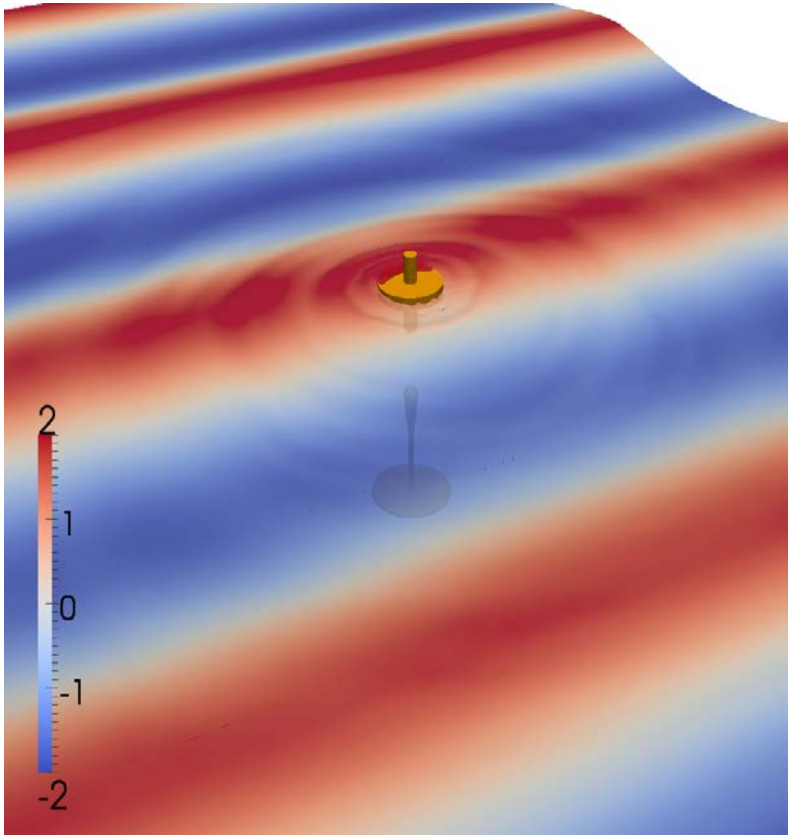
Device Part	Weight (Tones)	Weight %	Modeled Dimensions
Surface Float	173	28.6	20m Dia. x 4m
Vertical (Central) Column	187	30.9	6m Dia.
Reaction Plate	245	40.5	30m Dia.
Total	605		

Wave Tank Test and CFD Verification

Snapshot of experimental wave tank test (NREL/Pix 20367)



CFD Simulation using Star CCM+



Irregular Sea States Modeling

- **The model can be used to simulate wave energy converters in irregular (random) sea states.**
- **The dynamic model is used to estimate the annual averaged power production by superimposing multiple wave frequency components based on a general wave spectrum to:**
  - Compute a power matrix for the device in that general spectrum
  - The averaged annual energy production of the WEC system at a particular location can be obtained by multiplying the power matrix cell by cell with the joint probability distributions of sea states at any desired location.
- **References:**

  - Babarit, A. et al; “Numerical benchmarking study of a selection of wave energy converters,” Renewable Energy 41 (2012) 44-63.
  - Evans, D.V.; “A theory for wave power absorbing by oscillating bodies,” J. Fluid Mech. (1976), vol. 77, part 1, pp. 1-25.

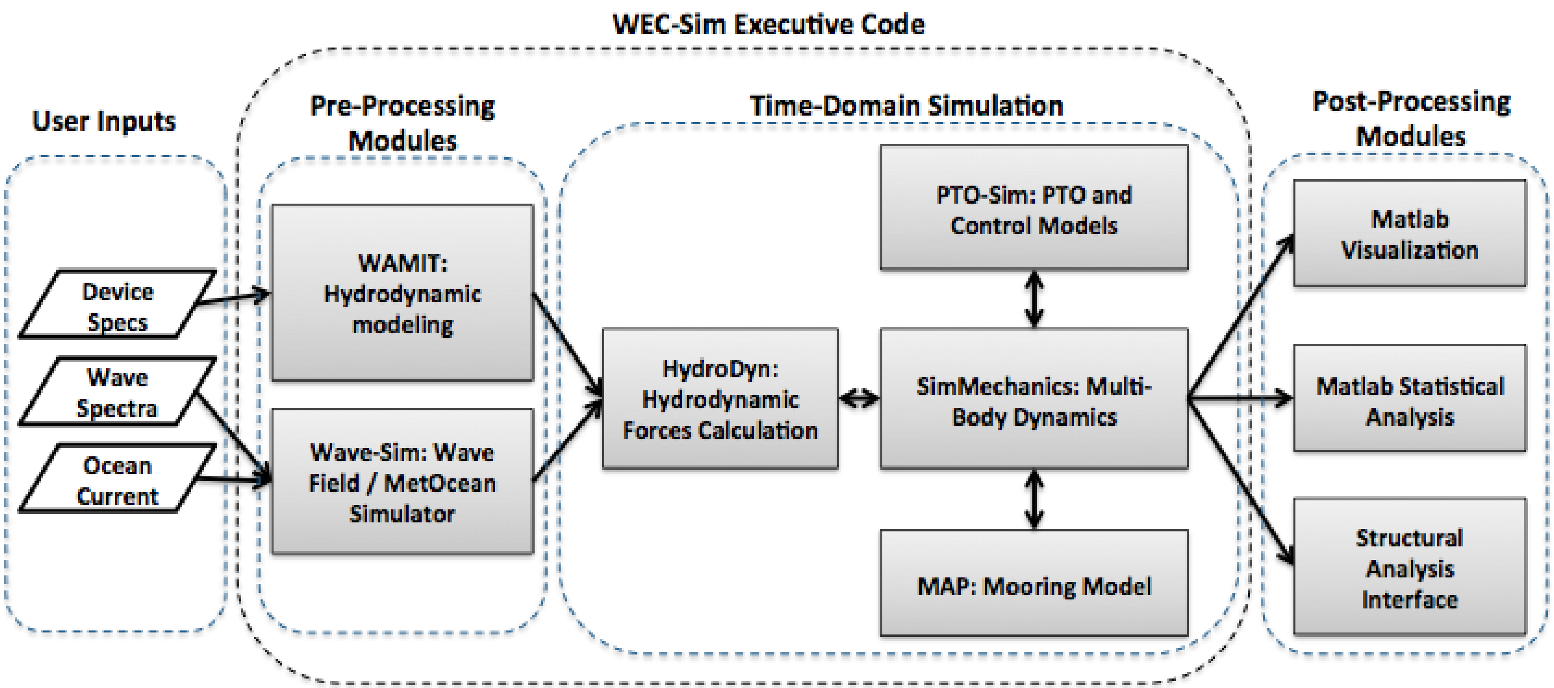
Wave Energy Converter Simulators

The Open Source Wave Energy Simulator WEC-Sim:

- A modular, WEC power performance code applicable for multiple WEC device geometries in 'operational' wave climates
- **OpenEI website** http://en.openei.org/wiki/WEC-Sim
- Developed jointly by the National Renewable Energy Laboratory and Sandia National Laboratory

Commercial Codes for Wave Converter Analysis:

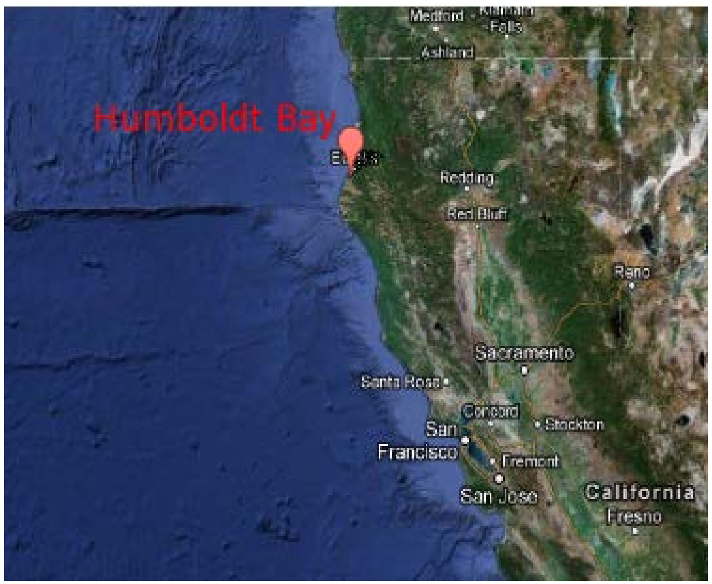
- **WaveDyn -** a wave energy converter performance and loading design tool. http://www.gl-garradhassan.com/en/software/WaveDyn.php
- **Re Vision -** Marine Renewables - device performance and structural loads. http://www.re-vision.net/
- **Orcaflex** - dynamic analysis of offshore marine systems. http://www.orcina.com/index.php
- **ANSYS AQWA** – Hydrodynamic Assessment. http://www.ansys.com



Wave Resource Near Humboldt Bay, CA

- **Joint Sea State Probability Distributions at Humboldt Bay California**
- **Mean wave energy flux: 31.2 (kW/m)**

Joint Probability Plot (%)													
	Peak Period (s)												
Hs (m)	5.7	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.7	14.7	15.7	16.7	17.7
0.25	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.75	0.4%	1.1%	1.1%	1.3%	0.4%	0.6%	0.3%	0.2%	0.2%	0.3%	0.4%	0.5%	0.2%
1.25	1.0%	2.8%	2.4%	4.6%	1.8%	2.2%	1.1%	0.9%	0.7%	0.5%	0.4%	0.4%	0.2%
1.75	0.2%	2.5%	2.7%	3.6%	2.1%	3.5%	1.9%	1.4%	1.2%	1.0%	0.5%	0.5%	0.3%
2.25	0.0%	0.6%	2.3%	3.6%	1.7%	3.3%	2.4%	1.9%	1.5%	1.0%	0.6%	0.5%	0.3%
2.75	0.0%	0.2%	0.9%	2.7%	1.0%	2.2%	2.0%	1.5%	1.3%	0.9%	0.5%	0.5%	0.3%
3.25	0.0%	0.0%	0.2%	1.1%	0.7%	1.2%	1.3%	1.2%	1.1%	0.8%	0.5%	0.4%	0.2%
3.75	0.0%	0.0%	0.0%	0.3%	0.3%	0.5%	0.7%	0.7%	0.7%	0.6%	0.3%	0.3%	0.1%
4.25	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.3%	0.3%	0.4%	0.4%	0.2%	0.2%	0.1%
4.75	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.2%	0.2%	0.1%	0.2%	0.1%
5.25	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%



X Cell by Cell

Power Matrix (kW) Cd_float=1.4; Cd_plate=4.25 (Based on CFD)													
	Peak Period (s)												
Hs (m)	5.7	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.7	14.7	15.7	16.7	17.7
0.25	0.42	0.71	0.97	1.19	1.36	1.46	1.49	1.45	1.36	1.24	1.11	0.99	0.87
0.75	3.77	6.36	8.75	10.73	12.22	13.14	13.38	13.02	12.21	11.17	10.03	8.91	7.85
1.25	10.51	17.66	24.32	29.80	33.96	36.49	37.17	36.15	33.92	31.02	27.86	24.74	21.80
1.75	21.66	34.79	47.66	58.41	66.55	71.52	72.85	70.86	66.49	60.80	54.62	48.49	42.73
2.25	37.64	61.75	79.03	96.55	110.02	118.23	120.43	117.14	109.92	100.50	90.28	80.16	70.64
2.75	57.95	100.66	121.83	144.23	164.34	176.62	179.90	174.98	164.19	150.13	134.87	119.74	105.52
3.25	81.24	150.37	178.99	204.14	229.54	246.68	251.27	244.40	229.33	209.69	188.37	167.24	147.38
3.75	108.16	209.85	249.53	279.77	306.79	328.42	334.52	325.38	305.32	279.18	250.78	222.66	196.22
4.25	138.93	272.93	332.45	371.07	399.54	421.84	429.68	417.93	392.17	358.59	322.12	285.99	252.04
4.75	173.54	340.92	426.99	477.32	509.06	530.38	536.73	522.05	489.87	447.92	402.37	357.24	314.83
5.25	212.00	416.47	531.26	597.80	634.90	655.75	657.31	637.74	598.43	547.19	491.54	436.41	384.60

Then sum all cells = Total extracted energy from waves

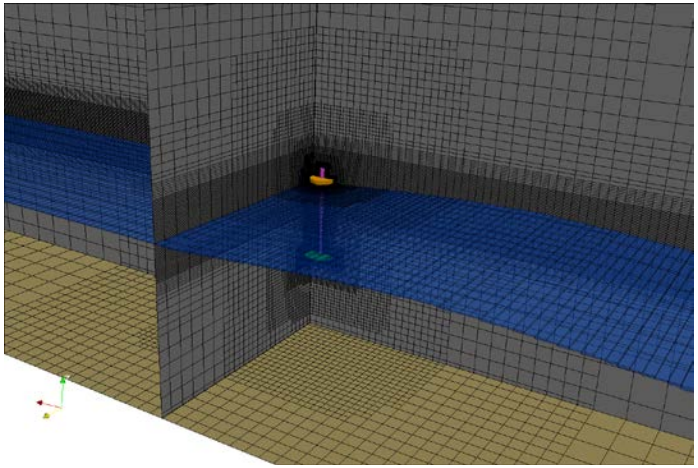
X Power conversion efficiency = Energy Produced

Extreme Wave Survival Loading Events

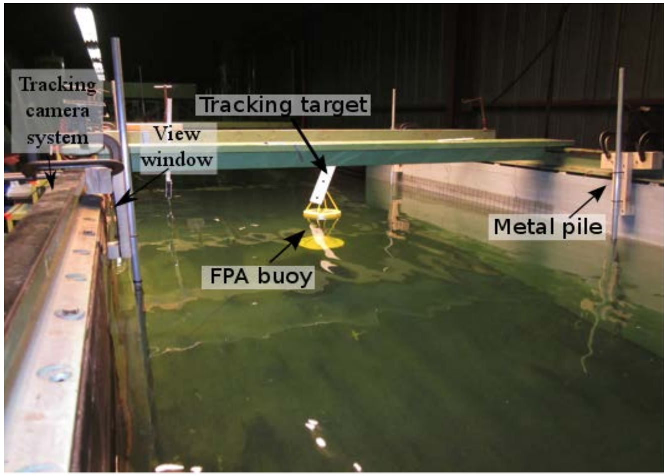
Extreme wave events at NDBC stations Northern, CA

Buoy number	Data period	MMWH (m)	50 years (m)		100 years (m)	
			$H_{s,50}$	95% CI	$H_{s,100}$	95% CI
46011	1980-2008	9.1	8.8	7.9, 9.5	9.1	8.0, 10.0
46012	1980-2008	8.7	8.9	8.2, 9.6	9.2	8.3, 10.1
46013	1981-2008	9.6	9.4	8.5, 10.2	9.7	8.7, 10.8
46014	1981-2008	9.8	10.2	9.4, 11.0	10.6	9.7, 11.5
46022	1982-2008	11.5	11.2	10.0, 12.3	11.6	10.2, 13.0
46023	1982-2008	8.0	8.1	7.7, 8.5	8.2	7.7, 8.7
46026	1982-2008	8.0	8.1	7.4, 8.7	8.3	7.5, 9.1
46027	1983-2008	9.6	10.3	9.4, 11.3	10.7	9.7, 11.9
46029	1984-2008	12.8	12.5	10.9, 14.0	13.0	11.1, 14.8
46041	1987-2008	11.4	11.2	9.8, 12.5	11.6	10.0, 13.3

Non-linear CFD simulation of survival scale waves

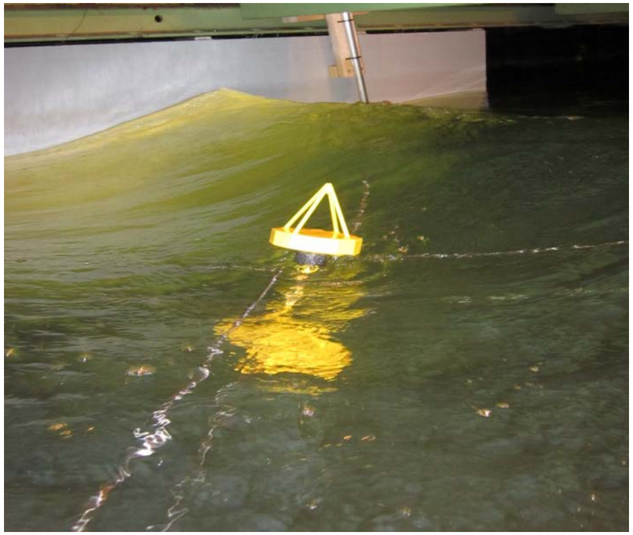


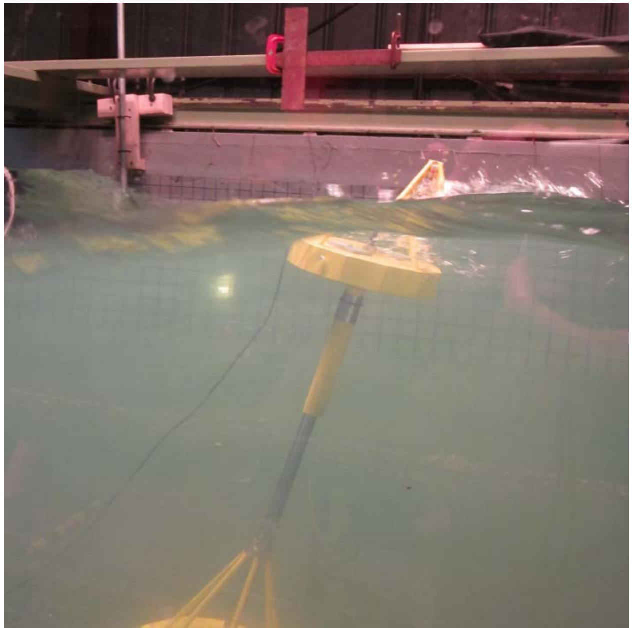
Wave tank testing in scaled survival waves (NREL Pic #20118)



Wave Tank Tests for Extreme Waves

- Pictures of testing of a 100th scale model in the UC Berkeley wave tank
- The float is locked in position for extreme events, because the device would not be producing power in large storm waves
- A motion tracking system is used to record the large motion dynamic response
- A small load cell is used to record the loads on the reaction plate
- The pictures show the float is sometimes completely out of the water and sometime totally submerged.
- Mooring lines where attached at two levels on the Buoy in an X configuration to stabilize the motion and limit rotation.

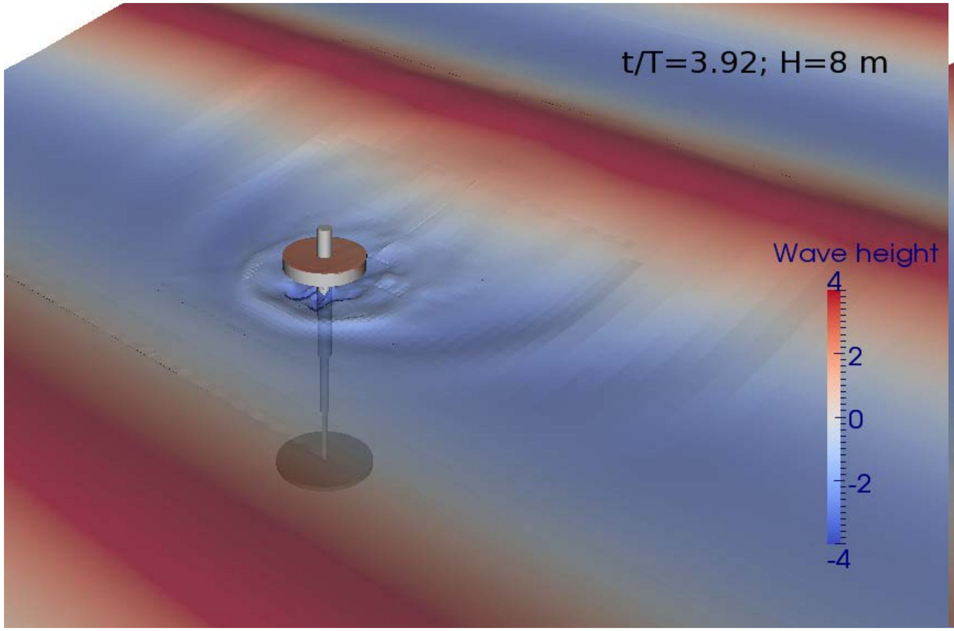




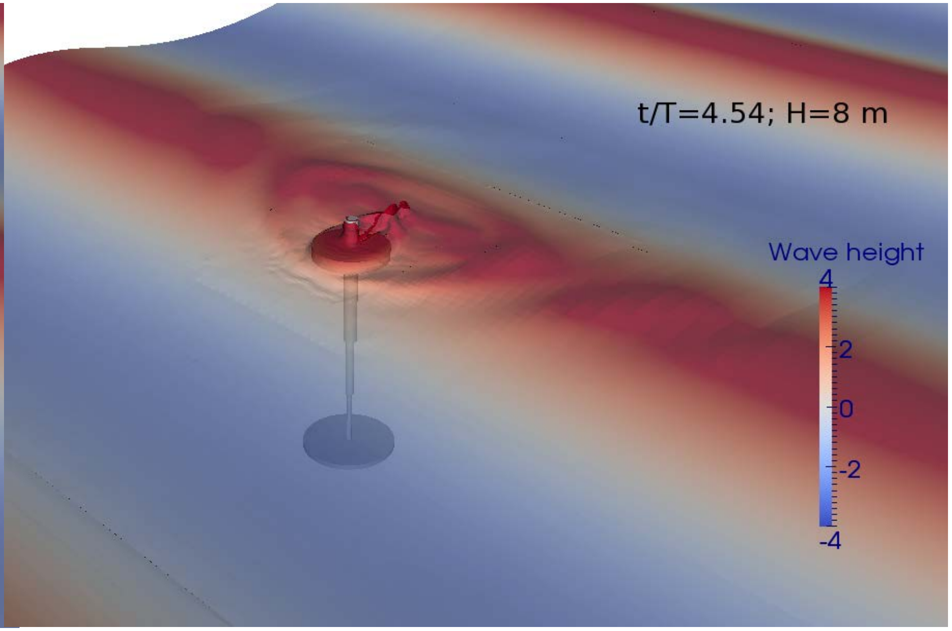
NREL Pics 20117 & 20118

Visualization of CFD Simulations

The visualizations compare favorably with the wave tank testing photographs



Buoy float out of the water



Buoy float under water

Array Effects for Wave Energy Converters

- **Understanding array interactions for a wave parks is an area of continuing research.**
- **A recent review of park effects had the following summary:**
  - Small arrays (5 to 10 devices) – The park effect can be neglected if the separation distance is 10xD or more.
  - Larger arrays (> 10 devices) – The park effect increases with the number of rows, and therefore the numbers of rows should be minimized the lateral spacing should be large.
  - Effect on the wave field – There is a small effect on the wave field that decreases with distance.
- **There are currently no large arrays deployed that could provide real world experience and information on preformance**
- **Reference:** Babrit, Aurelien, Ecole Centrale de Nantes, France; “A review of the park effect in arrays of wave energy converters.” Presentation at ICOE 2012 October 19th, 2012, Dublin, Ireland

Wave Technology Demonstrations and Deployments

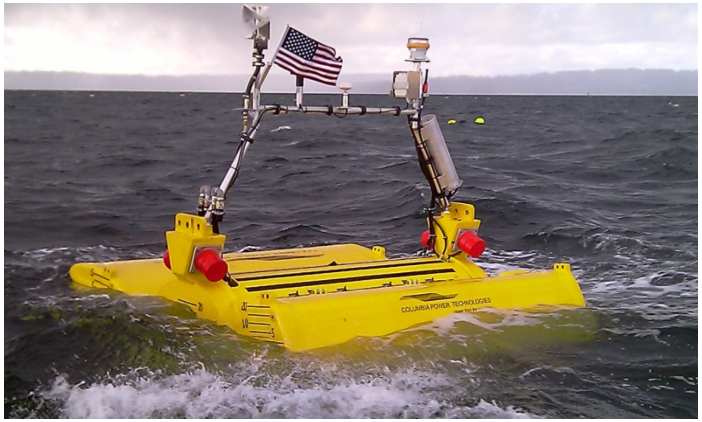
OPT PowerBuoy
(NREL Pic 17114)

Ocean Power Technologies

- Reedsport OPT Wave Park Project (1.5 MW)
  - First commercial license issued for a wave power project in the U.S. - August 13, 2012
  - 10 devices
  - 35-year *Commercial* Project License
- First grid-connected wave energy device in the U.S.

Columbia Power Technologies

- Deployed Wave energy converter in Puget Sound, WA. - March 2011
- Device recovered after ~11 months of continuous operation - March 2012
- 1/7 Scale Prototype

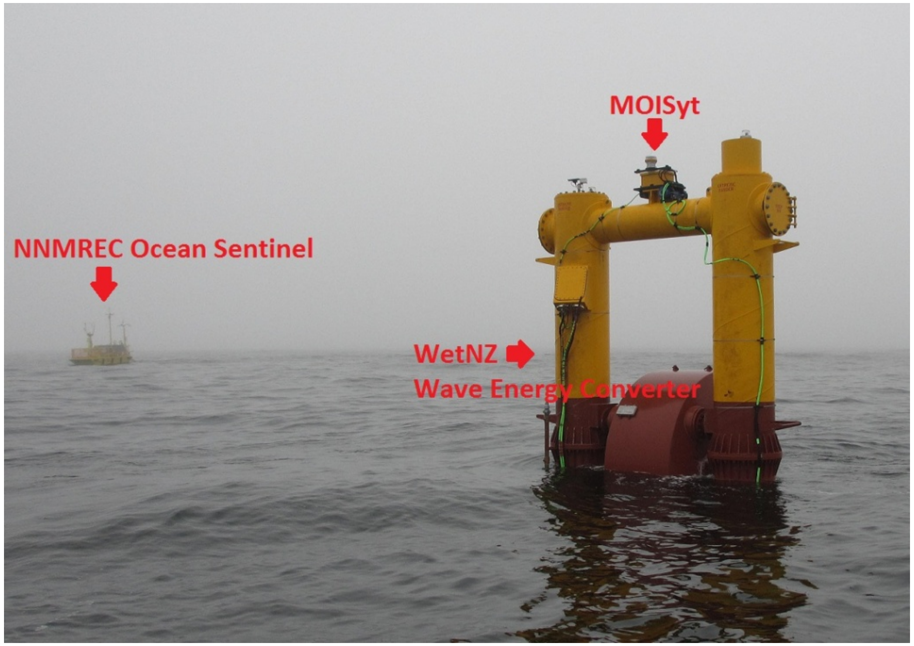


Columbia Power Technologies
(NREL Pic 19381)

Wave Technology Demonstrations and Deployments

Northwest Energy Innovations

- Oregon State University & Northwest National Marine Renewable Energy Center
  - Deployed Wave Energy Technology-New Zealand (WET-NZ) 1:2 scale wave energy conversion device - August 22^{nd}, 2012
  - Deployed the new $1.5 million Ocean Sentinel testing device
  - NREL MOISyt data system
- Navy's Wave Energy Test Site (WETS)
  - U.S. Department of Energy selected NWEI to test for 1 year at the Marine Corps Base Hawaii, in Kaneohe Bay - September 2012



WET-NZ under testing at the NNMREC Test Site August 2012 (NREL Pic)

National Marine Renewable Energy Centers

Northwest National Marine Renewable Energy Center:

The Oregon State University (OSU) in Corvallis, OR, and The University of Washington (UW) in Seattle, WA, are jointly running the Northwest National Marine Renewable Energy Center. The Northwest Center provides a full range of capabilities to support wave and tidal energy development for the U.S.

National Marine Renewable Energy Center of Hawaii:

The University of Hawaii in Honolulu, HI, established a center to facilitate the development and implementation of commercial wave energy systems in their state and to assist the private sector in moving ocean thermal energy conversion systems beyond proof-of-concept to pre-commercialization, long-term testing.

Southeastern National Marine Renewable Energy Center:

Florida Atlantic University has established a center to facilitate the development and implementation of ocean current systems and to assist in moving ocean thermal energy conversion systems and ocean water cooling systems research through testing and commercialization.

Moving Ahead with U.S. In-Water Testing Facilities

The US Navy is enhancing the capabilities of the existing **Wave Energy Test Site (WETS) at the Marine Corp Base in Hawaii (Keneohe Bay)**

- Berth @ 30m depth and grid connected (existing)
- Multiple deep Water Berths being developed at 60 m-70 m water depth and grid connected

Global Development Status of Ocean Energy

		CAPACITY [KW]	
COUNTRY	RESOURCE	INSTALLED	CONSENTED PROJECTS
Belgium	Wave power		*20000*
Canada	Tidal and ocean currents (and river current)	*250*	*5500*
	Tidal Range Power (Barrage)	*20000*	*0*
China	Wave Power	*190*	*2400*
	Tidal and ocean currents	*110*	*3700*
	Tidal Power	*3900*	*200*
Denmark	Wave Power	*250*	
New Zealand	Wave Power	*2 x 20 (one in Oregon)*	*220 (1 project)*
	Tidal Power	*-*	*21000 (2 projects)*
Netherlands	Tidal and ocean currents	*100*	*5000*
	Salinity Gradient	*10*	*50*
Norway	Salinity Gradient	*4*	
Portugal	Wave Power	*300 + 400*	
Republic of Korea	Wave Power		*500*
	Tidal and ocean currents	*1*	
	Tidal Power	*254*	
Spain	Wave Power	*296*	*140*
Sweden	Wave Power	*150*	*10000*
	Tidal and ocean currents		*7.5*
United Kingdom	Wave Power	*4,340*	*Various test deployments*
	Tidal and ocean currents	*6,700*	*Various test deployments*

Source: Annual Report Ocean Energy Systems Agreement of the IEA - http://www.ocean-energy-systems.org/

Cost of Energy for Wave Devices

- **The Carbon Trust in the UK has benchmarked first wave farm cost of energy at:**
  - 38 to 48 p/kWh (61 to 77 US cents/kWh) at a 15% discount rate and assuming a 20 year life.
- **They identify potential cost reduction areas:**
  - Energy capture improvements
  - Device structure
  - O&M
  - Installation
  - Power take-off
- **Reference**
  - The Carbon Trust Report – "Accelerating marine energy, The Potential for cost reduction – insights from the Carbon trust Marine Accelerator" July 2011.
  - http://www.carbontrust.com/resources/reports/technology/accelerating-marine-energy

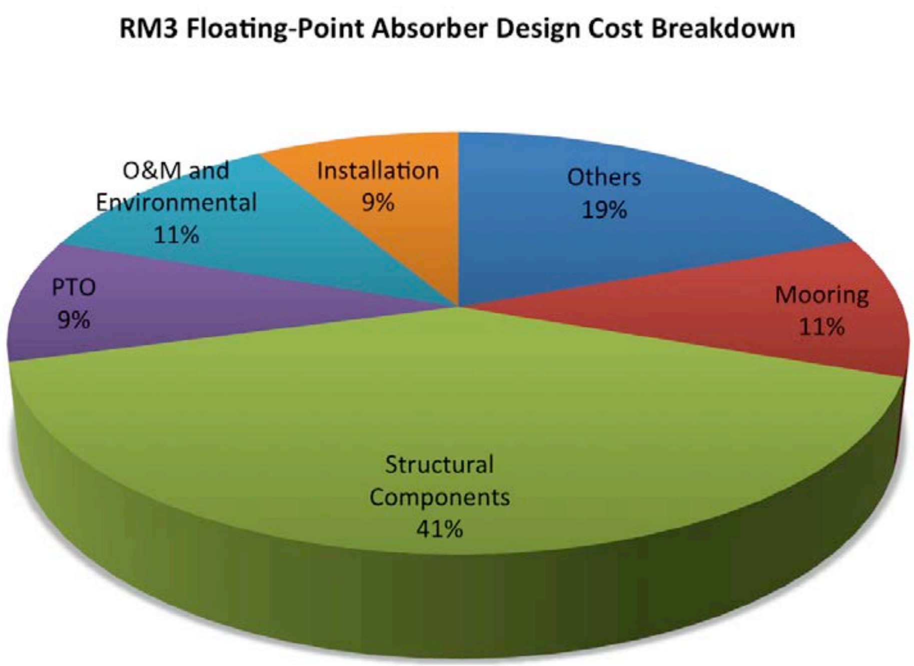
High Potential Cost Reduction for Wave Energy Converters

- **Advanced control strategies could increase energy capture by 2**

  [1] Eder, J.; Bretl, J.and Edwards, K. (2013). "Empirical Demonstration of Advanced Control Strategies for Wave Energy Converters," 32nd International Conference Ocean, Offshore and Arctic Engineering OMAE 2013, June 9-14, 2013, Nantes, France

  [2] Li, G., G. Weiss, M. Mueller, S. Townley, and M. R. Belmont, "Wave energy converter control by wave prediction and dynamic programming," *Renewable Energy*, vol. 48, no. 0, pp. 392–403, Dec. 2012.

- **Reduce the cost of material, mooring lines and PTO**



- **Very conservative structural design**
- **Similar to early day wind turbine design**
- **Wind turbines cost was reduced by a factor of ~ 3 over a decade**

DOE 2011 MHK Industry Project:
Active Acoustic Deterrence of Whales

Project Title: Active Acoustic Deterrence of Migratory Whales

PI: Greg McMurray, PEV

Partners: Oregon State University Marine Mammal Institute, Ocean Power Technologies, Tillamook Public Utility District, and Pacific Gas and Electric.

Objectives: Testing of a limited range acoustic deterrent system to discourage gray whales from entering wave energy parks and to minimize the risk of mortality. The project will test the effectiveness of an 'acoustic pinger' in the frequency range of 3-5 kHz at an amplitude of 60 dB above ambient noise. The project area is Yaquina Head, near Newport, OR.

Links to Lab Work: This is currently the Program's only work on mitigation strategies. Active acoustics could be tools used by labs in carrying out future research, and lessons learned in permitting and deploying this device could inform those studies.

DOE 2011 MHK Industry Project: Fish Strike Probabilities in Laboratory Tests

Project Title: Assessment of the Environmental Effects of Hydrokinetic Turbines on Fish: Desktop and Laboratory Flume Studies

PI: Paul Jacobson, Doug Dixon, EPRI

Partners: Alden Research Laboratory, USGS Conte Anadromous Fish Research Laboratory

Objectives: Determining the probability of blade strike and injury, and the behavior of fish as they encounter hydrokinetic turbines. (1) assessment of potential injury mechanisms using available data from conventional hydro turbines; (2) theoretical models for predicting blade strike probabilities and mortality rates; and (3) performing flume testing with at least three turbine designs and several fish species

Links to Lab Work: Data integrated into Tethys database on environmental research, and project overlaps with other work on physical interactions and effects on aquatic organisms.

DOE Sponsored MHK Environmental Research: at ORNL and ANL

Physical Interactions with Devices

- Evaluating potential for fish attraction and avoidance
- Modeling and experimentation to evaluate strike risk to fish

Electromagnetic Fields

- Experimentation to evaluate potential effects of EMF on fresh water fish and invertebrates

Acoustics

- Evaluating effects on MHK noise by increasing knowledge of noise in riverine environments. Planned device noise measurements and net-pen studies.

Toxicity

- Experimentation to measure the effects of antifouling coatings on aquatic organisms

Benthic Habitat Alteration

- Development of measurement methodology to evaluate effects of MHK devices on benthic habitat. planned measurements around devices.

Argonne NATIONAL LABORATORY

Conceptual Model Development

- Development of conceptual models to increase understanding of the ecological relationships between MHK stressors and biological receptors and the cumulative impacts of development.

Benthic Habitat Alteration

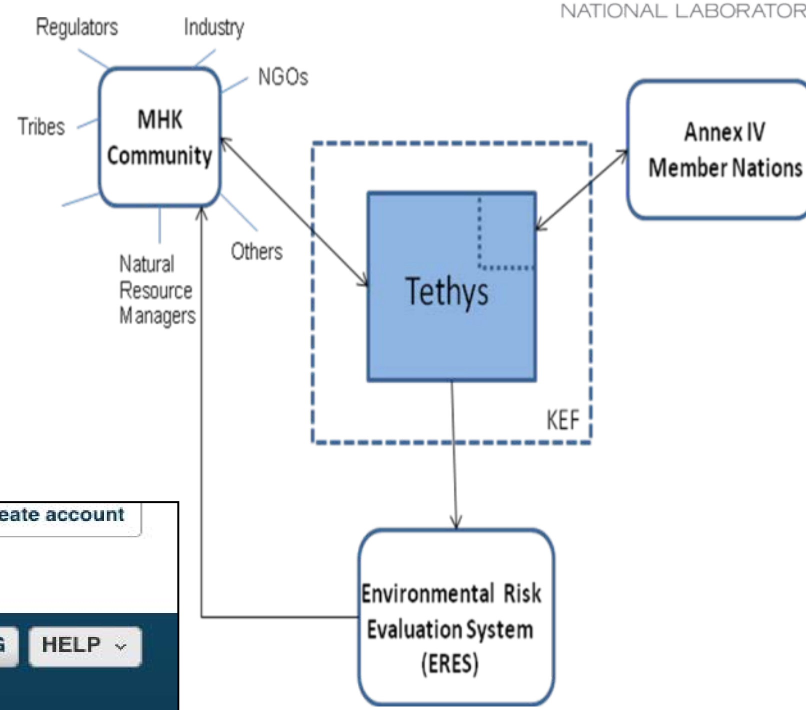
- Development of monitoring protocols

DOE Sponsored MHK Environmental Research:

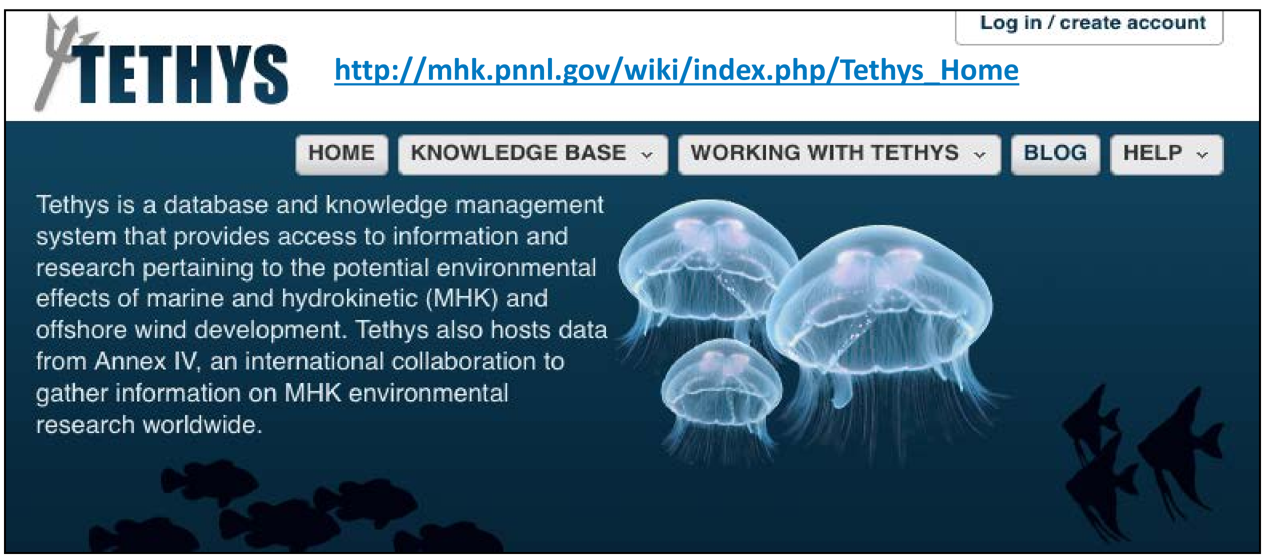
Knowledge Management System

- ***Challenge:*** Organize & make available information on environmental effects of MHK development
- ***Approach:*** Knowledge Management System, publically available & easily accessible
- ***Outcome:*** Shared knowledge to accelerate siting & permitting

Pacific Northwest NATIONAL LABORATORY



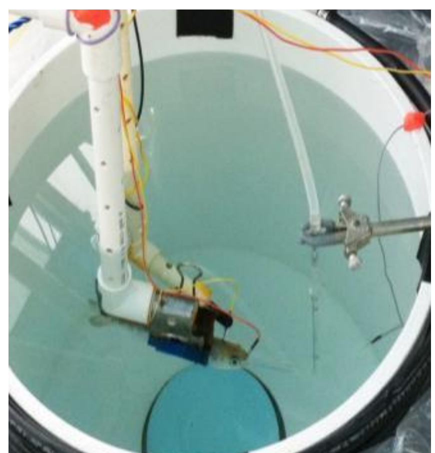
Schematic of *Tethys* relationship with analysis tools (represented by ERES) & stakeholders

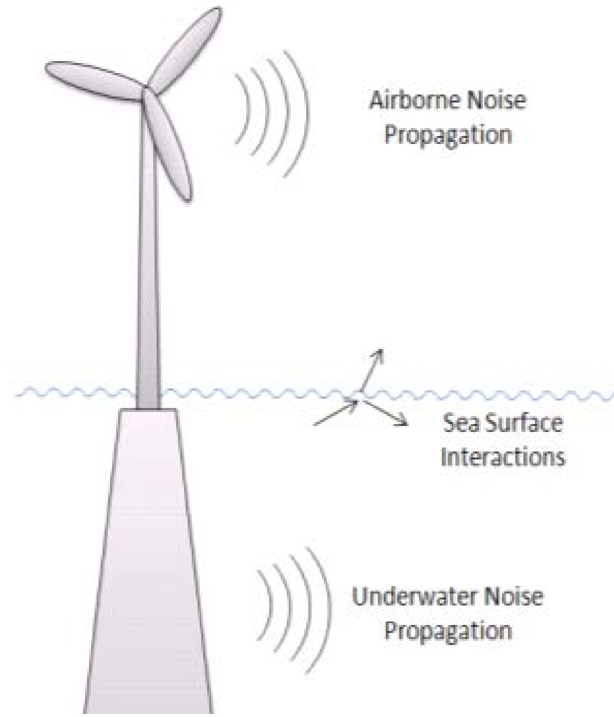


Courtesy of Jennifer States

DOE Sponsored MHK Environmental Research: Knowledge Gaps in Stressor/Receptor Interactions

- **Priority laboratory and field experiments:**
  - High risk interactions
  - High level of uncertainty
- **Acoustic interactions for MHK & wind turbines**
  - Lab testing to measure acoustic impacts on fish
  - Modeling offshore wind overwater/underwater
- **Electromagnetic fields from underwater cables**
- **Improved information:**
  - Add into TETHYS
  - Improve risk estimates though ERES



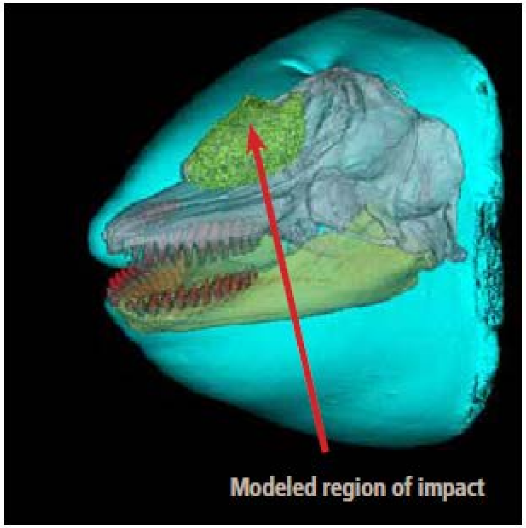


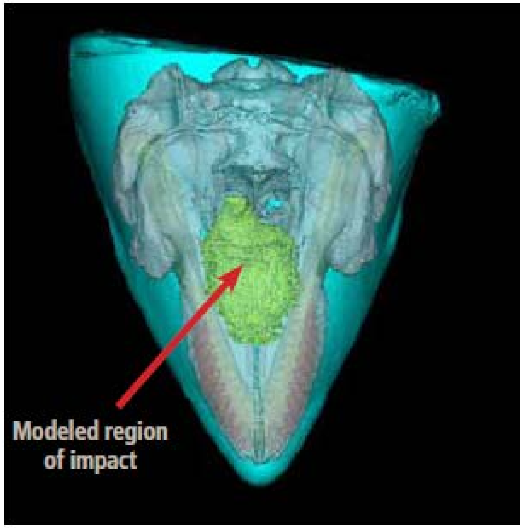
Courtesy of Jennifer States

DOE Sponsored MHK Environmental Research: Mitigating Risk to Endangered Species

Severity of Strike Analysis

- ***Challenge:*** Risk to SRKW from tidal turbines is a major barrier to permitting tidal power development in Puget Sound.
- ***Technical Approach:*** PNNL and Sandia National Laboratories modeled the forces caused by a turbine blade striking a SRKW and evaluated potential damage to the whale.
- ***Outcome:*** The models show that harm to the SRKW would be minimal or equivalent to a bruise. NOAA Fisheries is evaluating the information; Snohomish PUD has filed for a final license application with FERC.





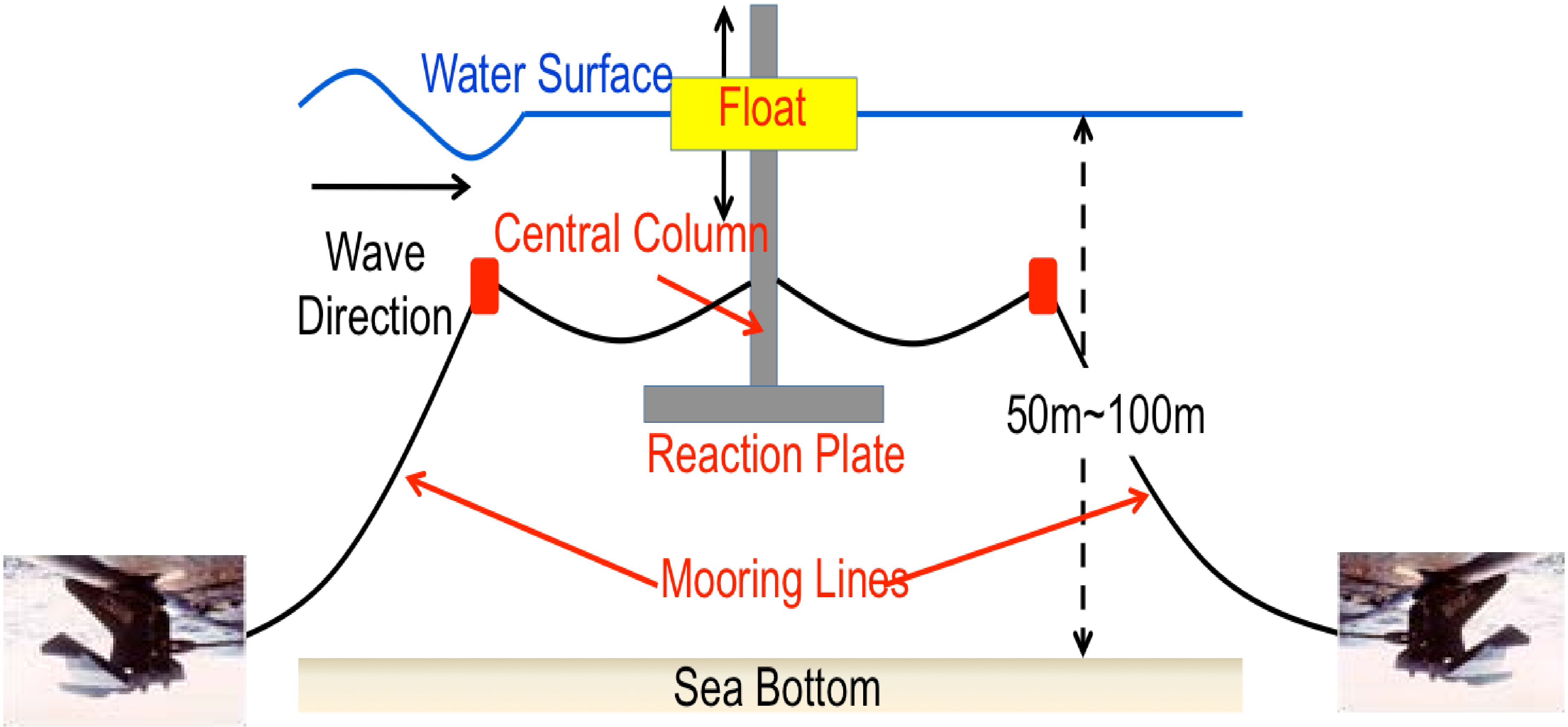
CT scan of an adult female SRKW that died in 2002. The side view (left) and the top view (right) show the internal structure of the head including the teeth (red), bone (grey), mellon (green), and other tissues. The region that was modeled to estimate impact from a turbine blade is indicated by the red arrows.

Courtesy of Jennifer States

Pacific Northwest NATIONAL LABORATORY

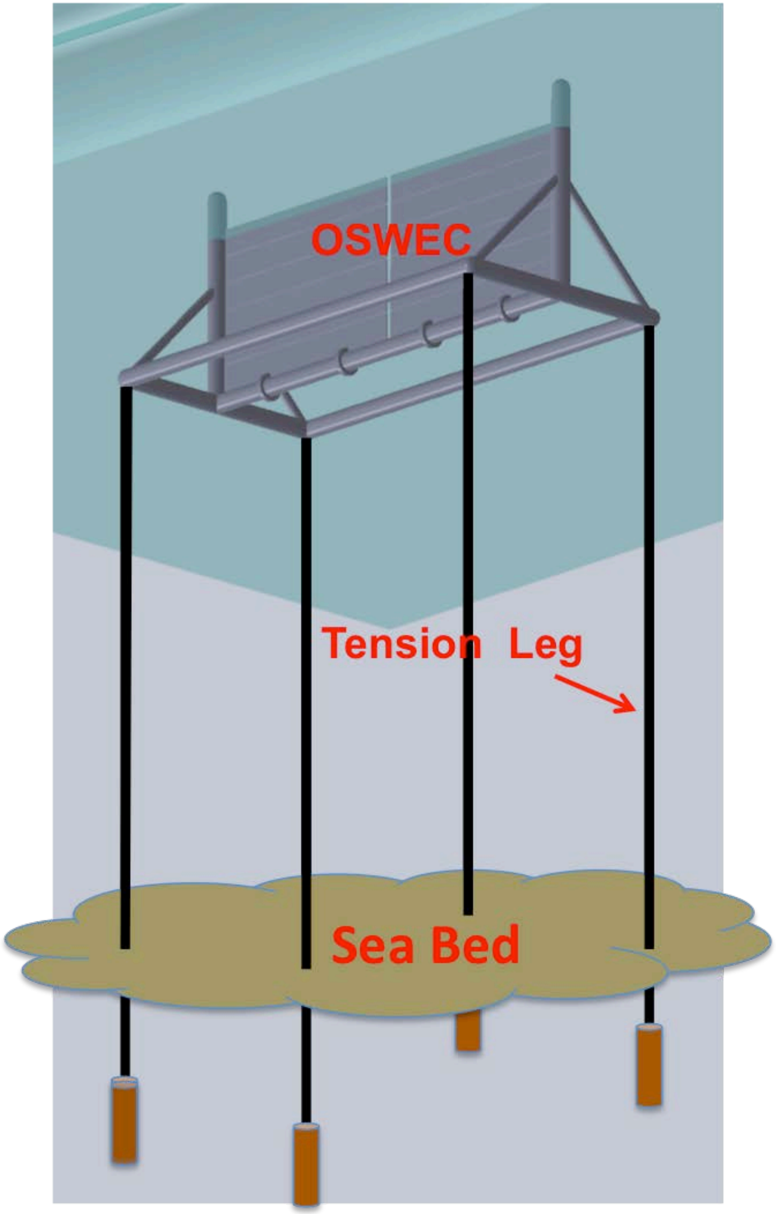
Sandia National Laboratories

Drag Embedment Anchoring



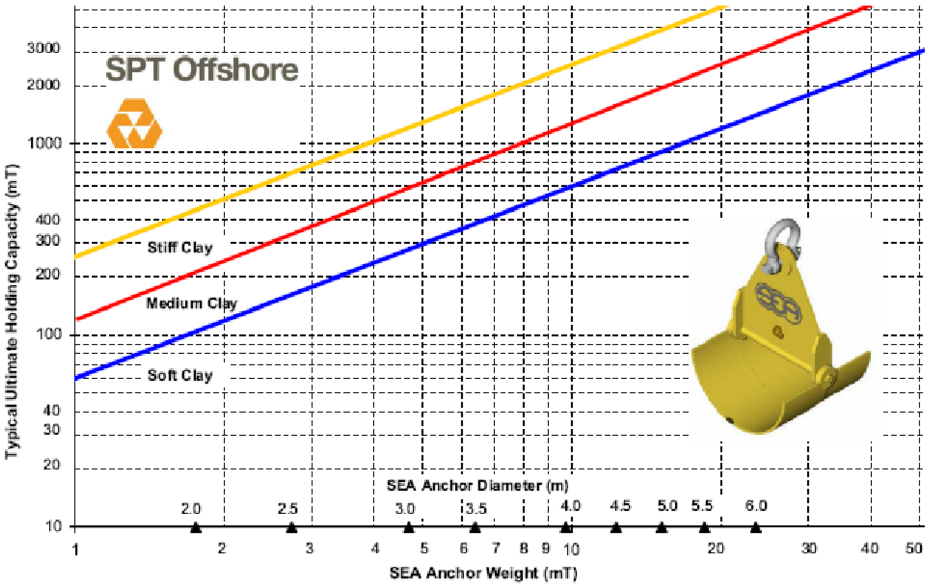
Mooring and Anchoring

- **Similar to tension leg platform (TLP)**
- **Design specifications:**
  - Mooring type: tension legs (tendons)
  - Mooing line: steel pipe
  - Anchor type: suction embedded anchors

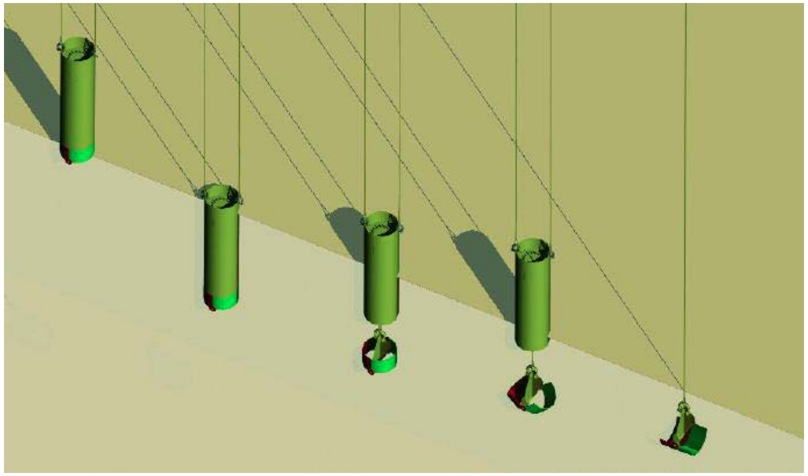


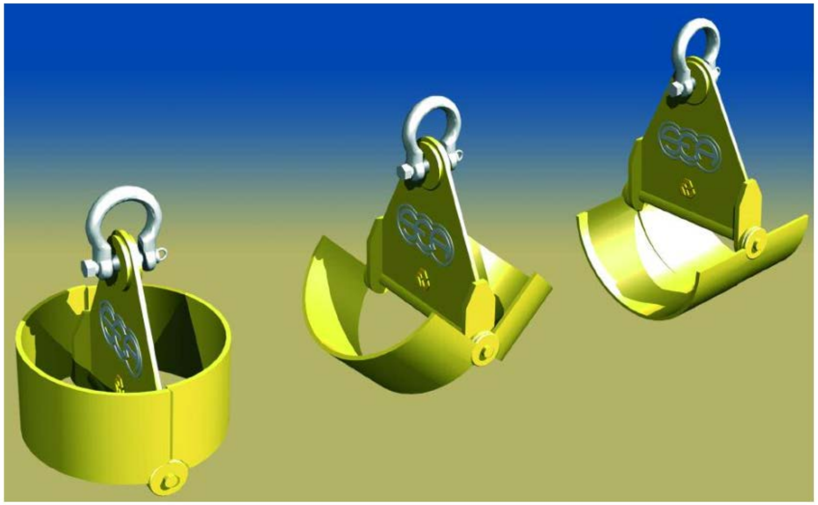
Mooring and Anchor Design

- **A suction embedment anchor was selected to secure tendons to the seabed (also used in RM4 ocean current turbine design).**

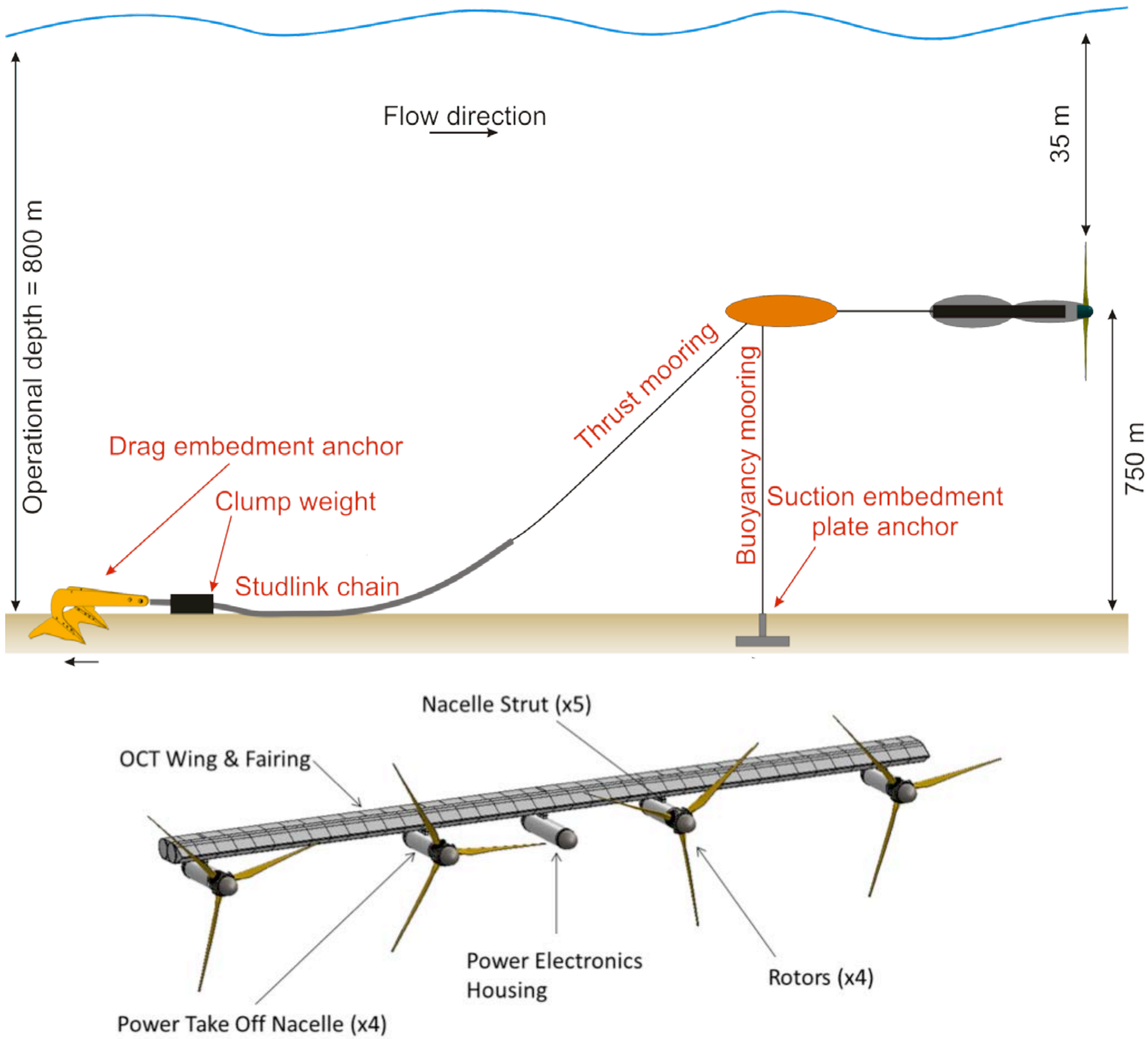


hcp://www.sptoffshore.com

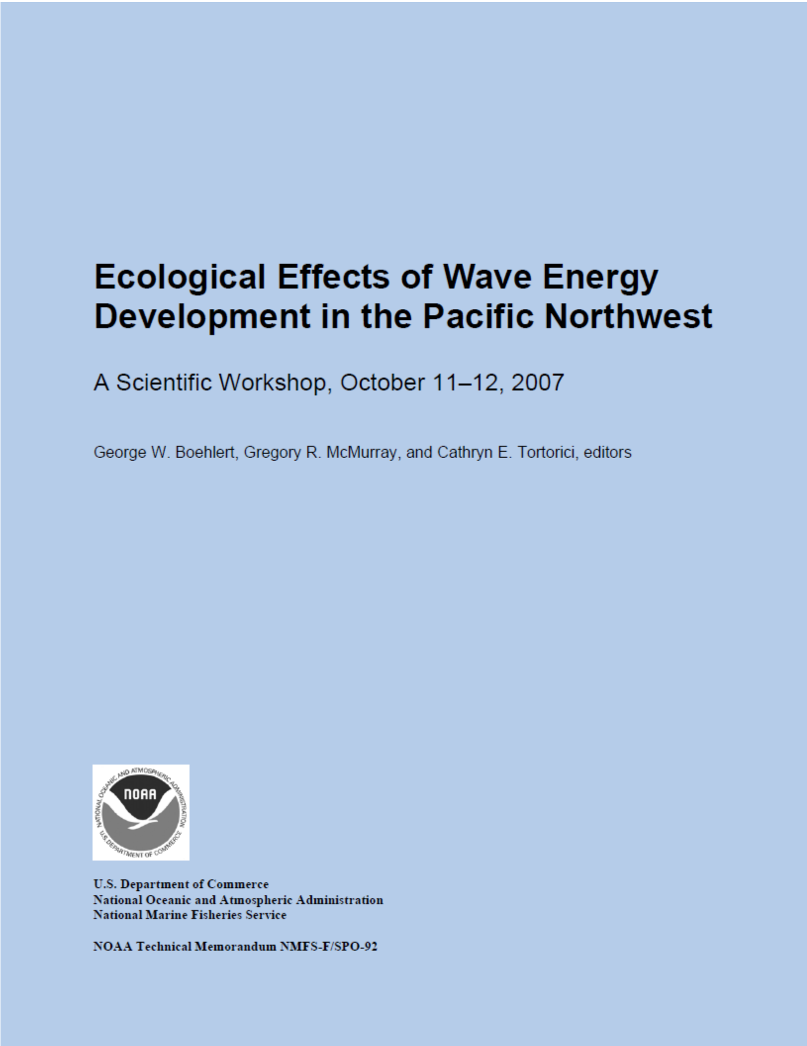




Ocean Current Concept



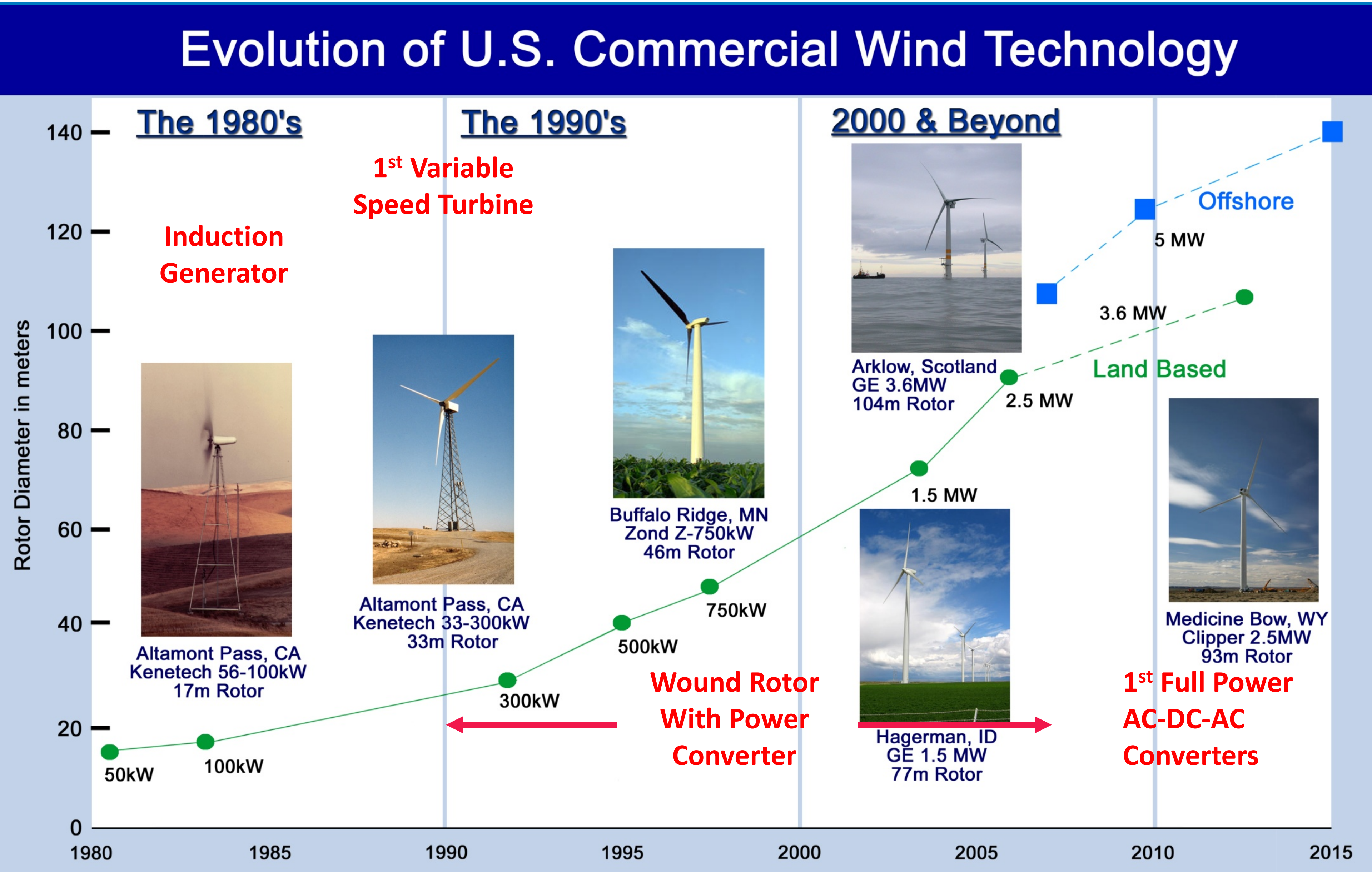
Important Documents on Offshore Environmental Impacts



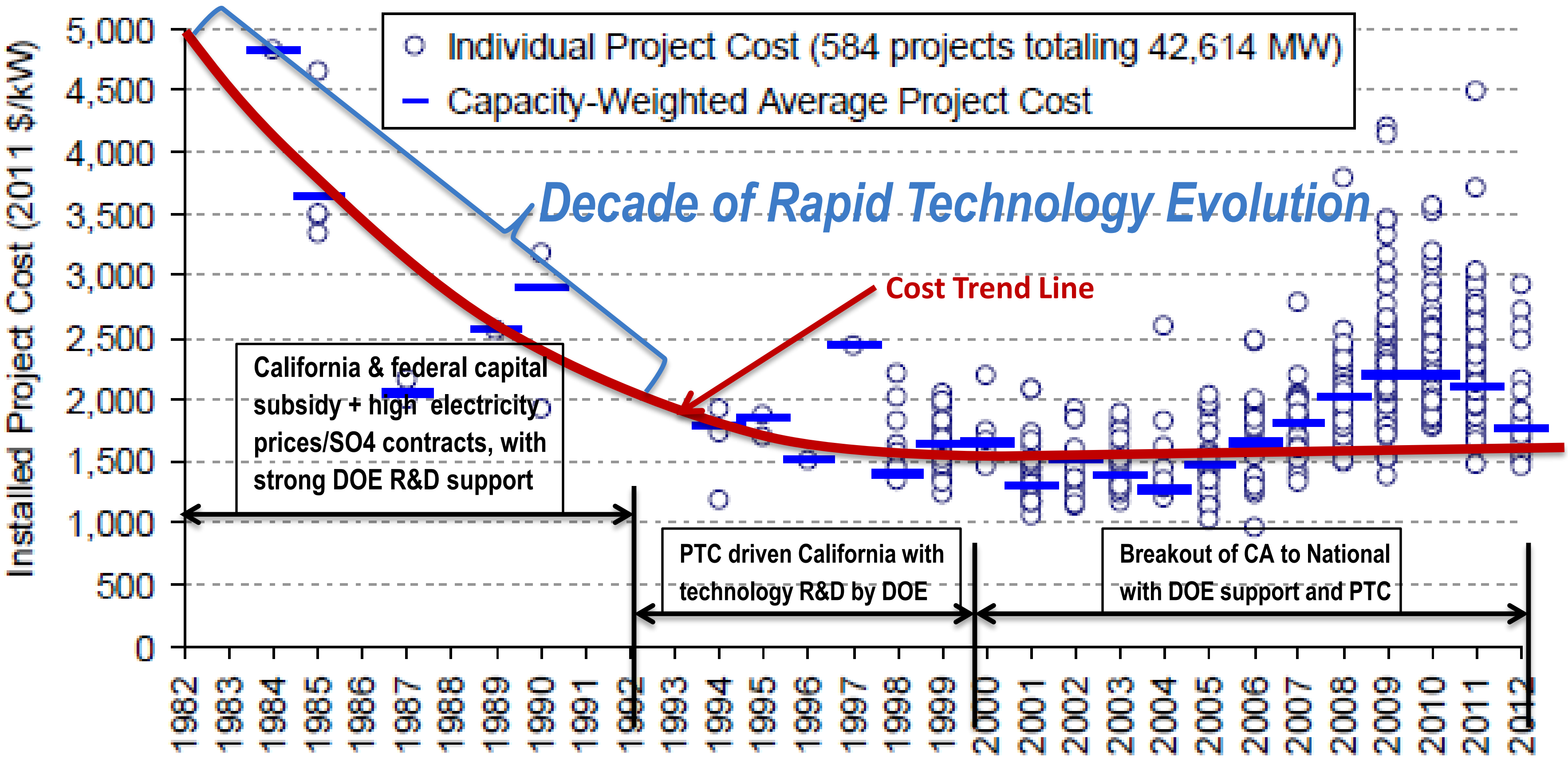
http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/9426/Wave%20Energy%20NOAATM92.pdf?sequence=1

http://193.88.185.141/Graphics/Publikationer/Havvindmoeller/havvindmoellebog_nov_2006_skrm.pdf

How Wind Technology Evolved Over Time



How did wind technology enter the market?

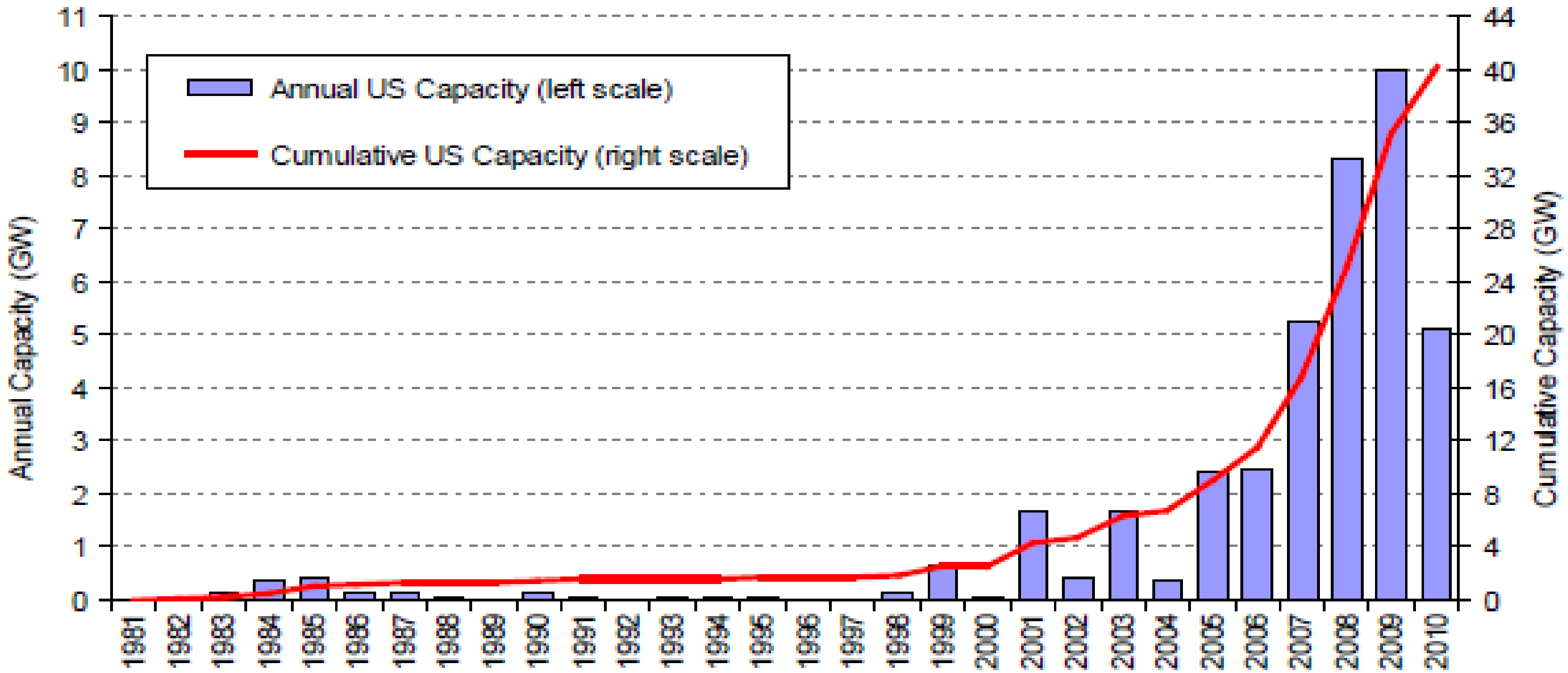


Note: 2012 data represent preliminary cost estimates for a sample of 20 projects totaling 2.6 GW that have either already been or will be built in 2012, and for which substantive cost estimates were available.

Source: Berkeley Lab (some data points suppressed to protect confidentiality)

MHK technologies may follow a similar pathway!

Wind was a Boutique Industry Until 2000

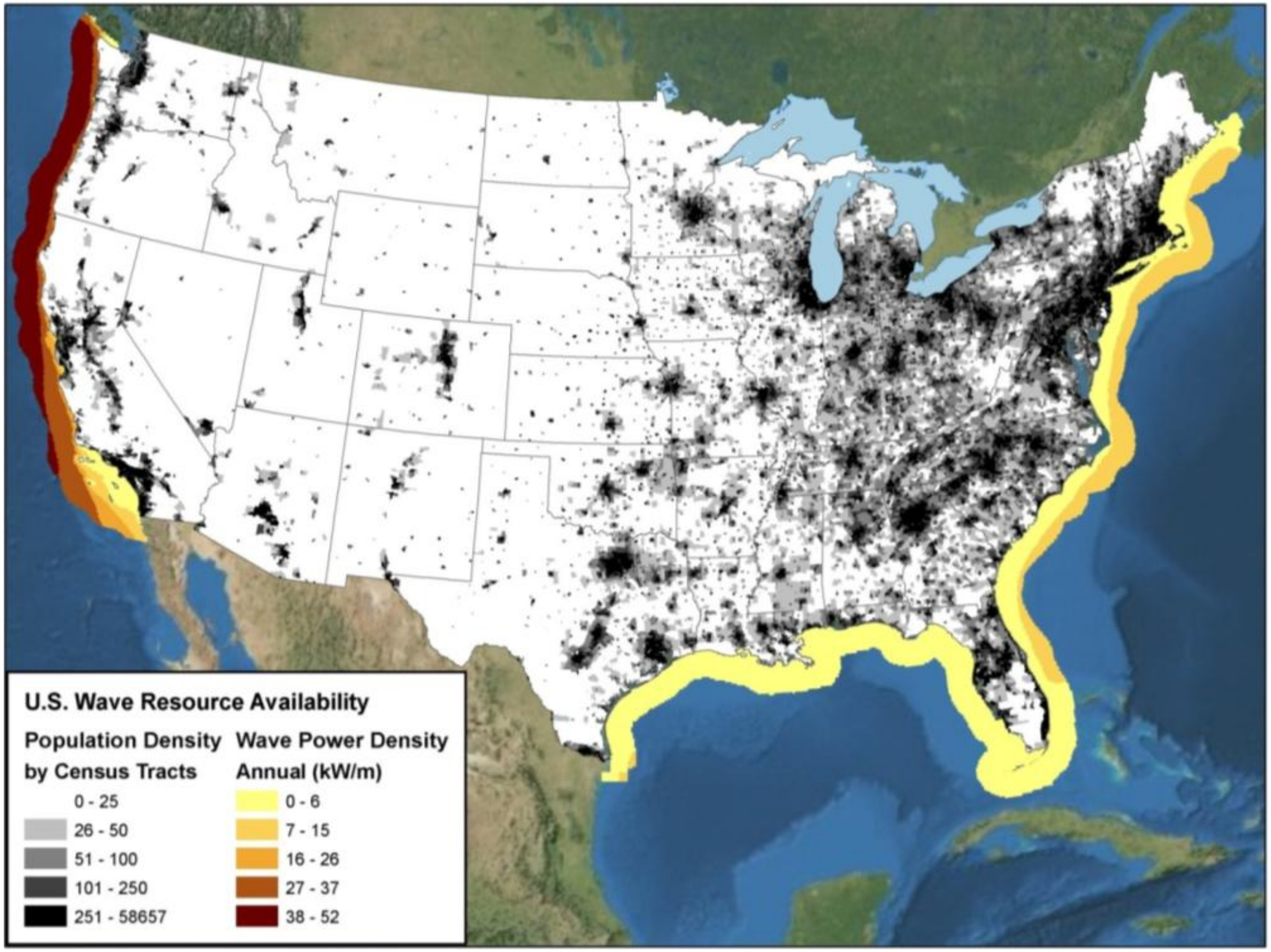


Source: AWEA project database

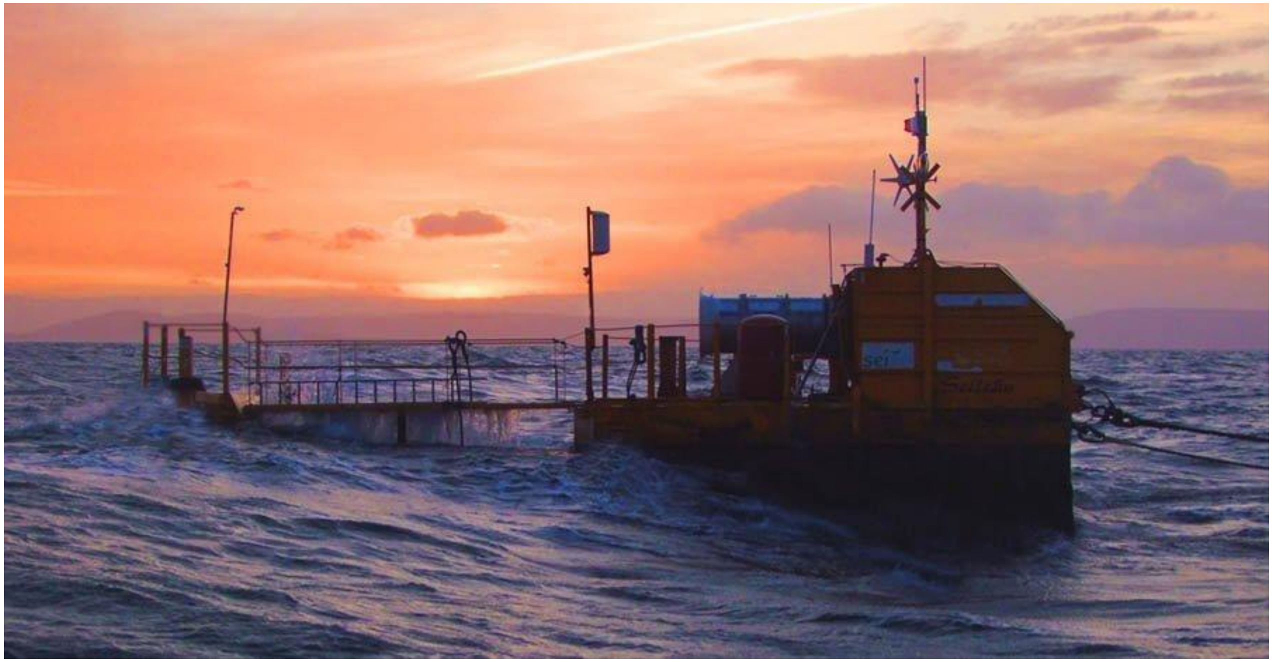
Figure 1. Annual and Cumulative Growth in U.S. Wind Power Capacity

Wave Resources are Abundant off the California Coast

California led the way in the development of wind energy!
California could again lead in the development of wave energy!



Questions?



NREL Pics #17873

Robert Thresher, NREL Research Fellow
Robert.Thresher@nrel.gov