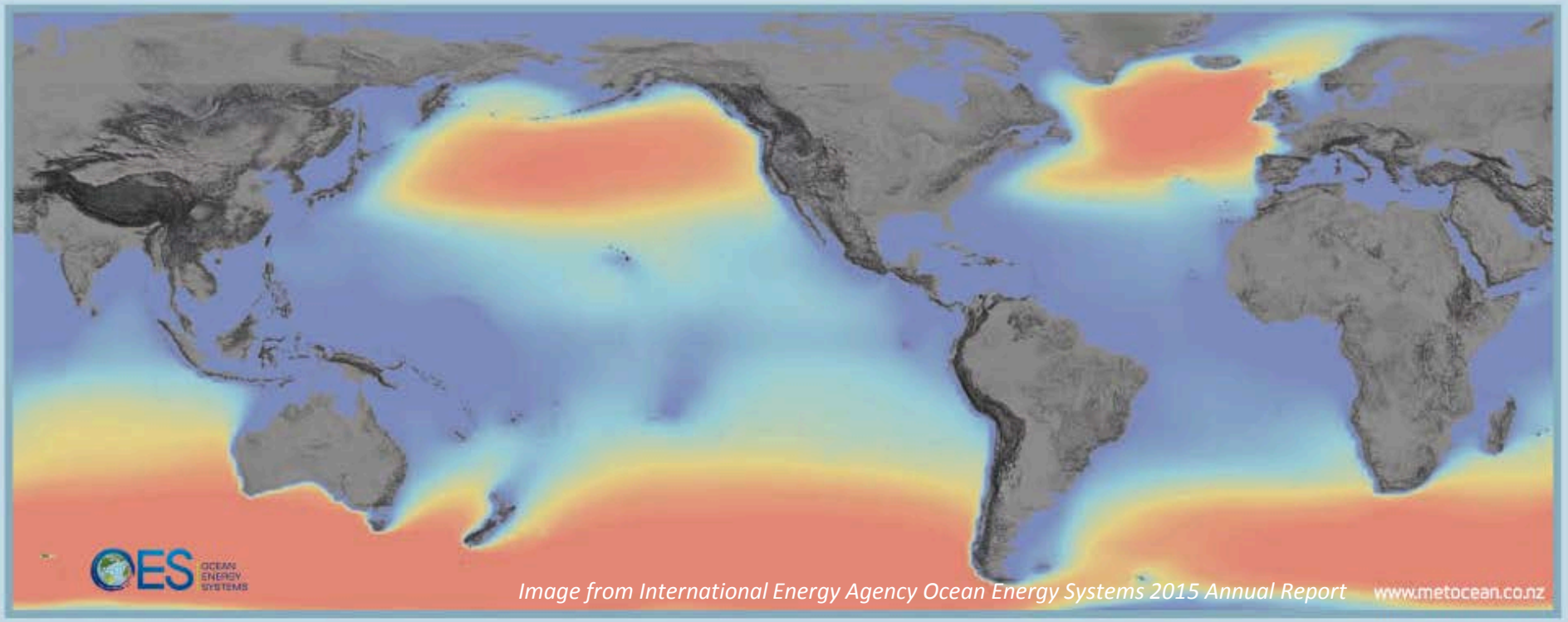
NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Wave Energy Technology Overview

Al LiVecchi

Laboratory Program Manager

Water Power

November 1, 2016

California Ocean Renewable Energy Conference

Outline

- Global Wave Energy Overview
  - Global resource and activities
  - International Standards
  - Supply chain/opportunity
  - Utility Scale Generation
  - Non utility scale/off grid applications
  - Desalination
  - Device archetypes
  - Economics

- Wave Energy Converter Research and Development
  - Process
  - Simulation/design
  - Laboratory testing
  - Ocean testing

Global Wave Energy Deployment Snapshot

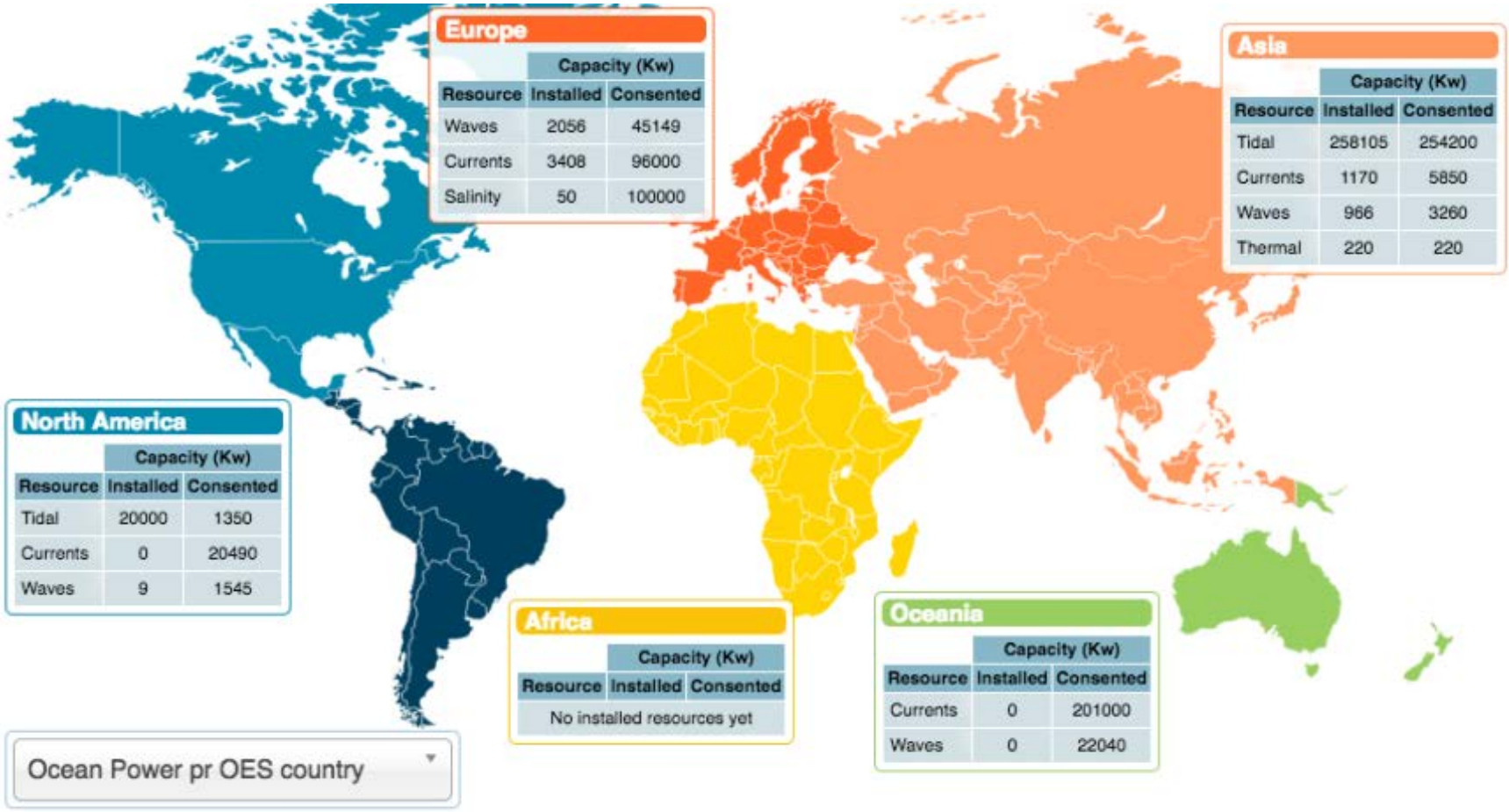


Figure from International Energy Agency Ocean Energy Systems 2015 Annual Report

Conformity Assessment For the MHK Industry

Objectives of Conformity Assessment

- Identify, classify and reduce risk
- Provide assurance to stakeholders
- Open global markets

"Mechanics" of Conformity Assessment (Certification)

- Based upon International Standards (IEC, ISO, etc.)
- 3rd party verification undertaken by "Certifying Bodies" is "Certification"
- 1st and 2nd party verification also exist (Ex. Self-declaration)

Certification is <u>CRITICAL</u> to the advancement of the MHK industry

- Reduce perceived risk
- Improved access to funding, insurance, etc.
- Single global certificate on International Standards (consensus based)

Utility Scale Farms with Shared Balance of Station


Photo from Columbia Power Technologies


Photo from Oscilla Power


Photo from Northwest Energy Innovations


Image from Carnegie Wave Energy Ltd.

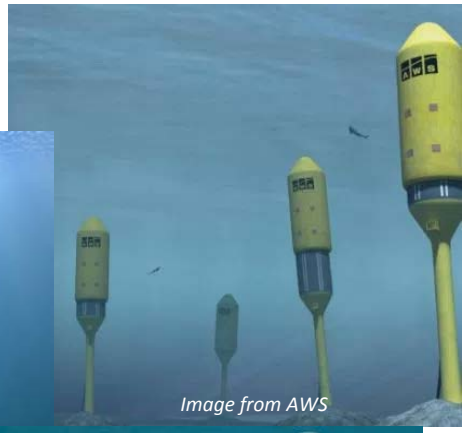


Image from AWS

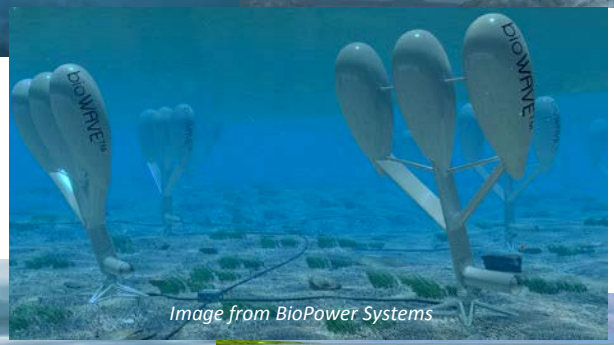


Image from BioPower Systems


Image from Pelamis Wave Power


Image from Ocean Power Technologies

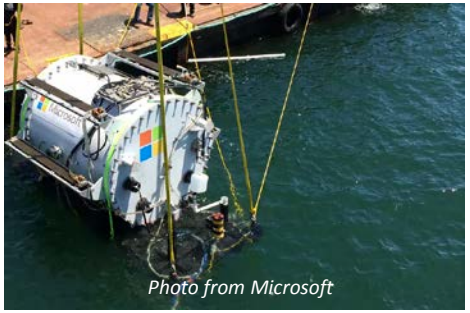
Now – Prototype Deployments → **Goal** – Utility Scale Wave Farms

Potential Non-Utility End Uses and Markets

- Remote coastal/island communities
- Energy security/resiliency – disaster, military
- Autonomous power
- Ports/Erosion control
- Aquaculture
- Data farms
- Desalination

OPT PowerBuoy3
Autonomous Power Unit

European OWC Wave Power Plant, Azores



Microsoft Underwater Data Farm

WaveNET Aquaculture Generator Units

Desalination Through Pressure or Electricity

Carnegie Wave CETO

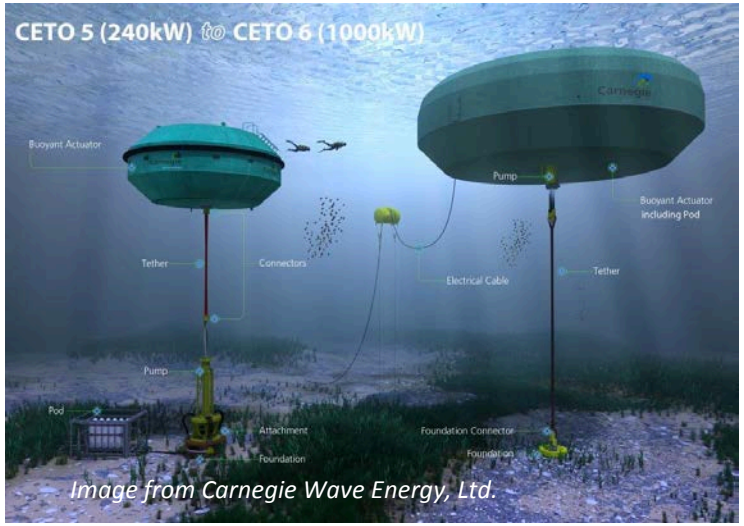


Image from Carnegie Wave Energy, Ltd.

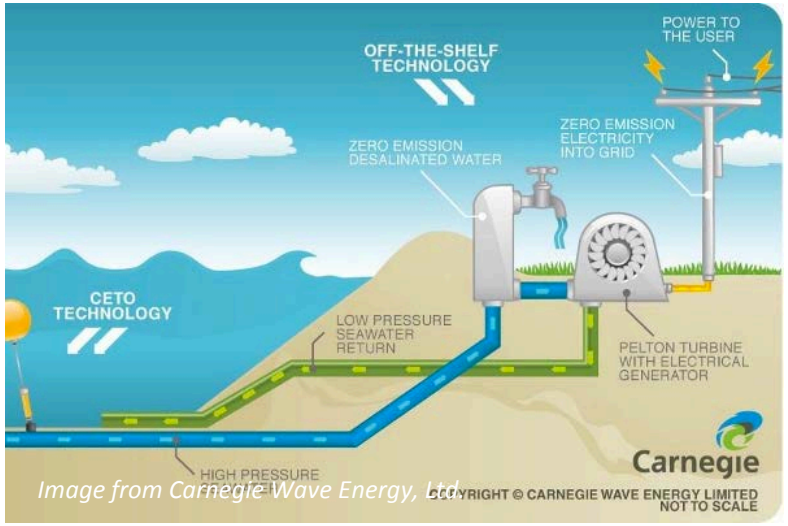


Image from Carnegie Wave Energy, Ltd.

Resolute Marine Energy

Photo from Resolute Marine Energy

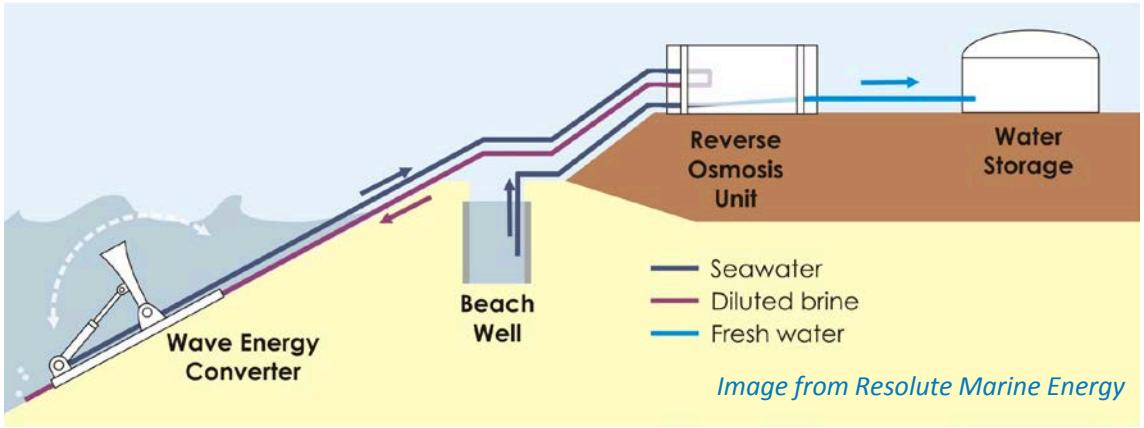
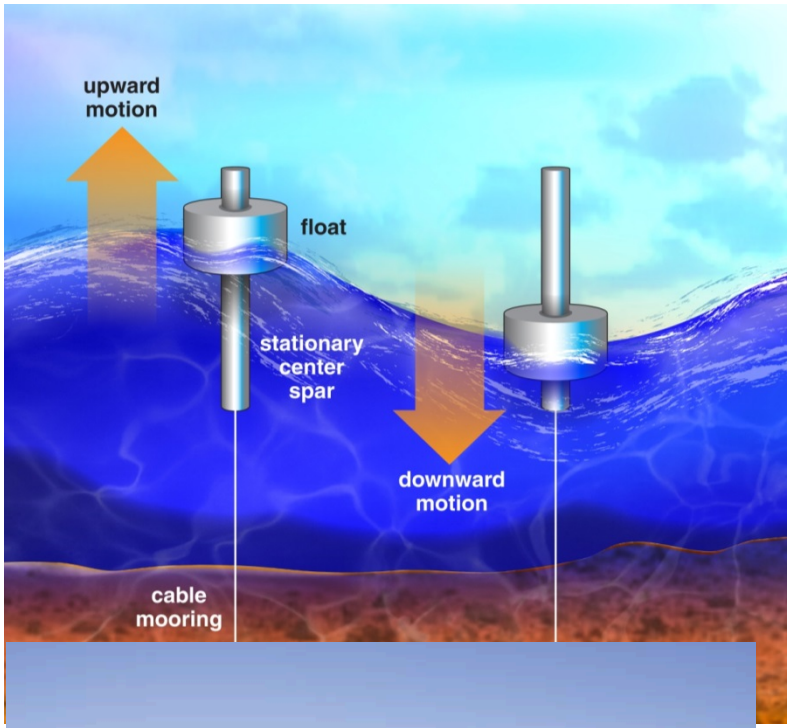


Image from Resolute Marine Energy

Point Absorber Buoys

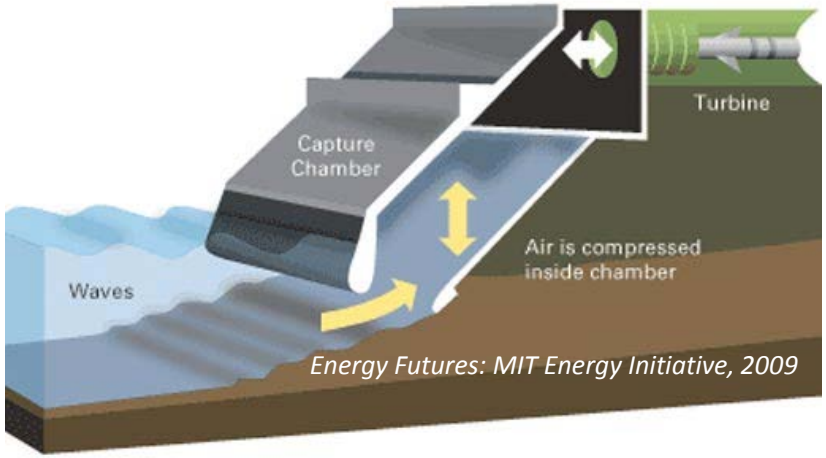


Key operation concepts:

- Floats on the surface
- Device pitches and heaves
- Single or multiple floats move relative to stationary spar or hull structure
  - Rotary
  - Linear
- Moored to seabed (>50m depth)
- Some bottom fixed devices
- Electric or hydraulic generators

Figures from Renewable Energy Futures Study NREL TP-6A20-52409-2

Oscillating Water Column



Key operation concepts:

- Onshore fixed or floating
- Floating devices pitches and heaves on or near surface
- Structure above the water, air turbine generator (e.g. 500 rpm)
- Moored to seabed (>50m depth)

Attenuator

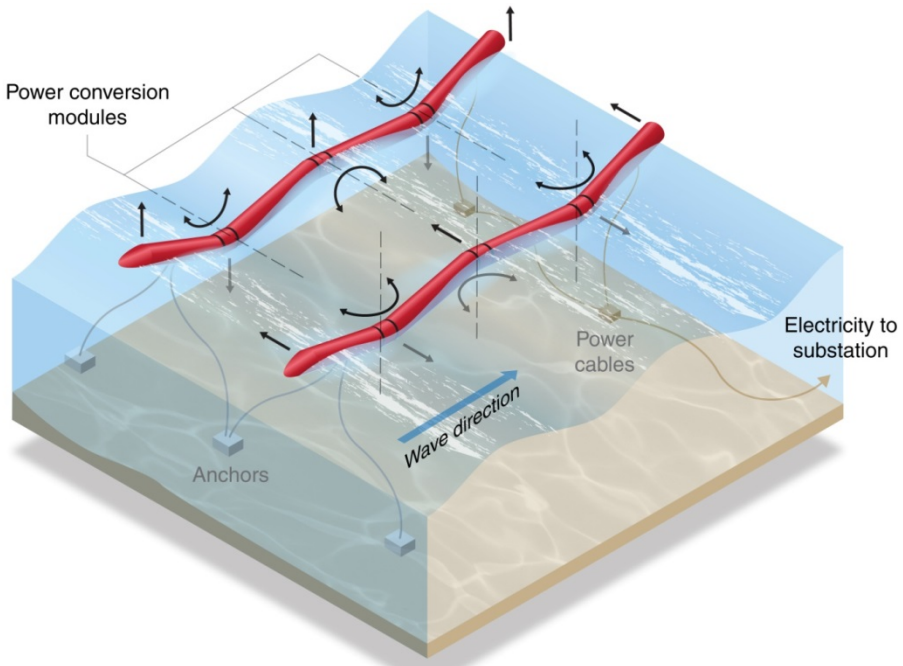


*Figure from Li Y., and Yu Y.-H., 2012, "A Synthesis of Numerical Methods for Modeling Wave Energy Converter-Point Absorbers," Renew. Sustain. Energy Rev., **16**(6), pp. 4352–4364.*

Key operation concepts:

- Floats on the surface, most of the device near the surface
- Multiple float sections move relative to each other
- Device orients to wave direction
- Long devices (upwards of 180m)
- Moored to seabed (>50m depth)
- Electric or hydraulic generators
- Watch circle from orienting with waves

Terminator - Inverted Pendulum

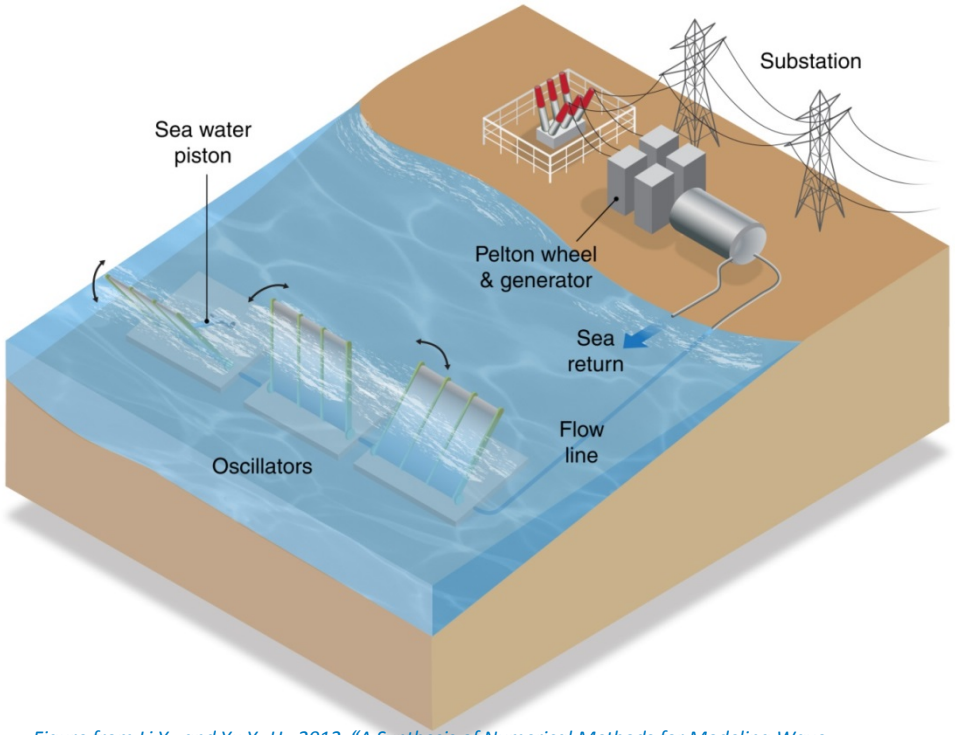


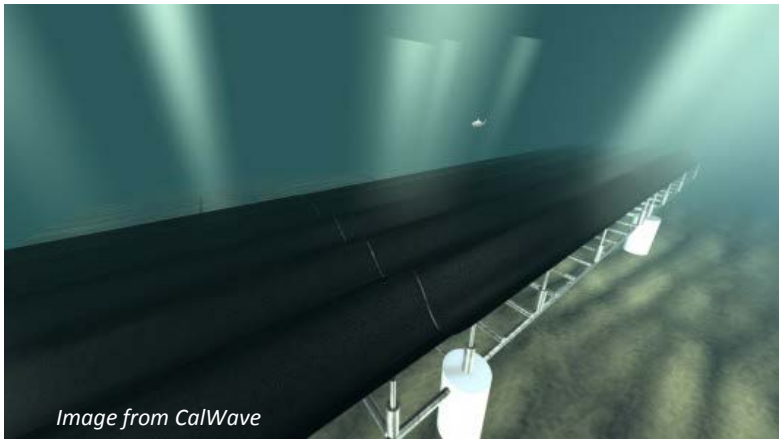
*Figure from Li Y., and Yu Y.-H., 2012, "A Synthesis of Numerical Methods for Modeling Wave Energy Converter-Point Absorbers," Renew. Sustain. Energy Rev., **16**(6), pp. 4352–4364.*

Photo from Resolute Marine Energy

Key operation concepts:

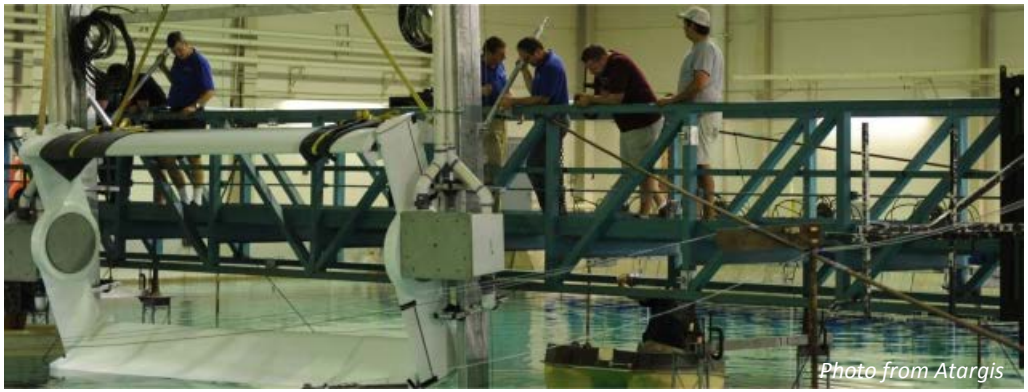
- Rests or anchored to seabed, < 50m depth
- Devices rock back and forth
- Likely to be deployed in a linear array, surface parallel to shore
- Can occupy much of the water column
- Typically operate close to the surface to maximize oscillatory motion
- Electric or hydraulics pumped to shore
- Floating concept for greater depth

New Design Concepts are Emerging



WaveCarpet – Submerged wave energy absorber surface

M3 – Submerged communicating volumes absorber



Atargis – Rotating foil lift driven absorber

Infrastructure, Capabilities, and Economic Impacts

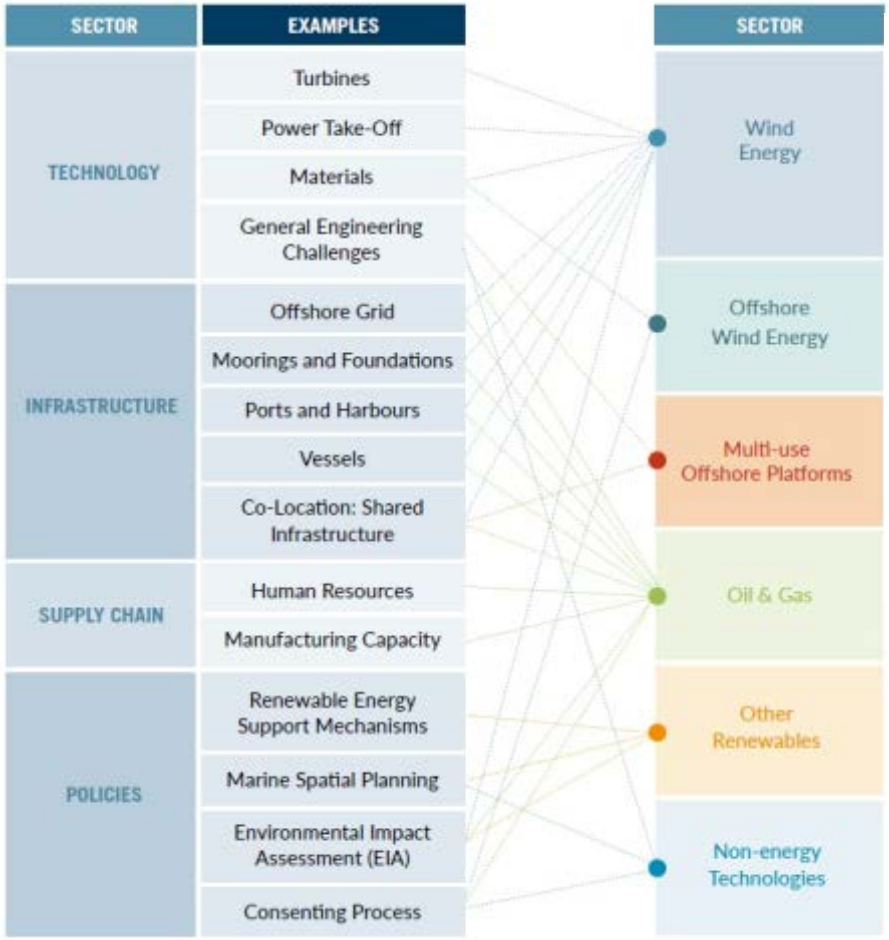


Figure from International Energy Agency Ocean Energy Systems 2015 Annual Report

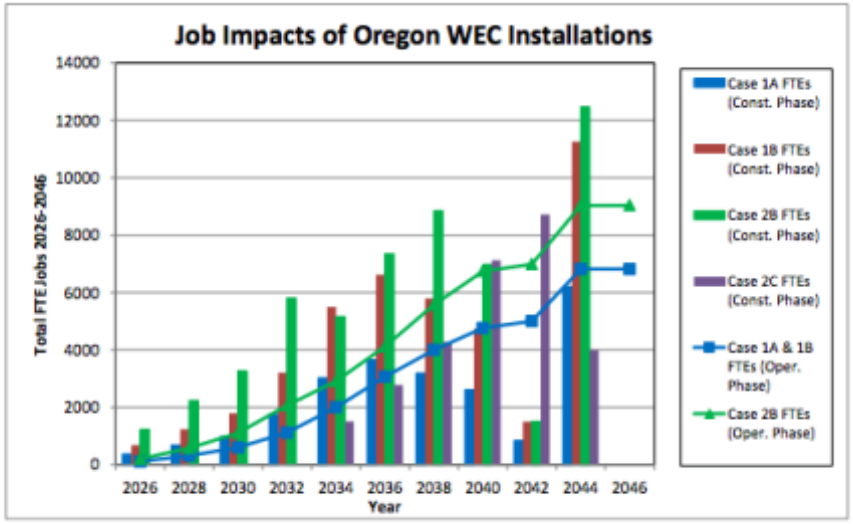


Figure ES-2. Estimated jobs from large-scale WEC deployment in the State of Oregon

Figure from Economic Impact of Large-Scale Deployment of Offshore Marine and Hydrokinetic Technology in Oregon Coastal Counties, T. Jimenez, S. Tegen, and P. Beiter, National Renewable Energy Laboratory

Wave Energy Costs and Reduction Objectives

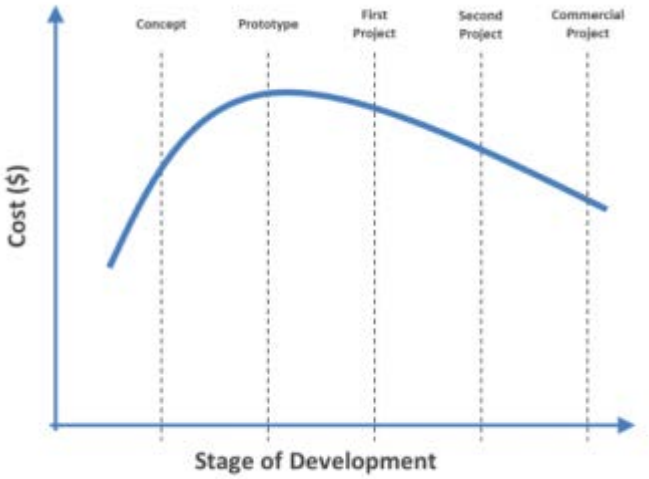


Figure 1: Project cost as a function of development stage

Deployment Stage	Variable	Wave	
		Min	Max[1]
First array / First Project[2]	Project Capacity (MW)	1	3 [3]
	CAPEX ($/kW)	4000	18100
	OPEX ($/kW per year)	140	1500
Second array/ Second Project	Project Capacity (MW)	1	10
	CAPEX ($/kW)	3600	15300
	OPEX ($/kW per year)	100	500
	Availability (%)	85%	98%
	Capacity Factor (%)	30%	35%
	LCOE ($/MWh)	210	670
First Commercial-scale Project	Project Capacity (MW)	2	75
	CAPEX ($/kW)	2700	9100
	OPEX ($/kW per year)	70	380
	Availability (%)	95%	98%
	Capacity Factor (%)	35%	40%
	LCOE ($/MWh)	120	470

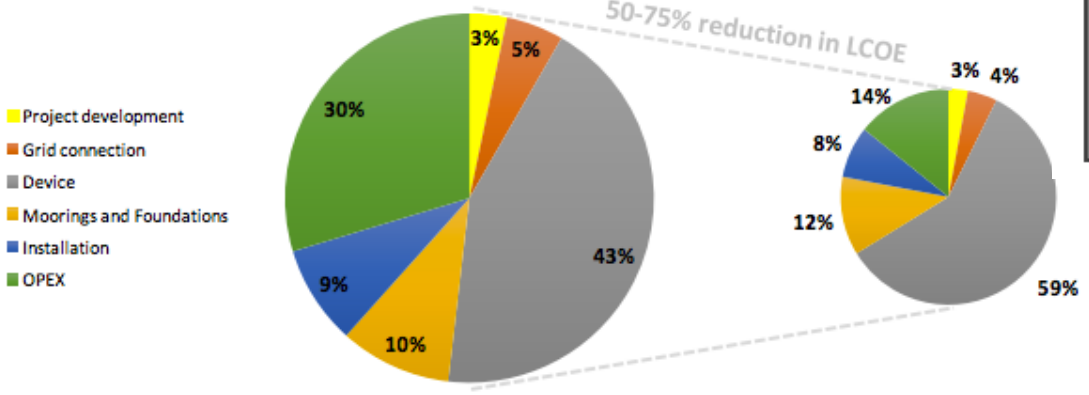
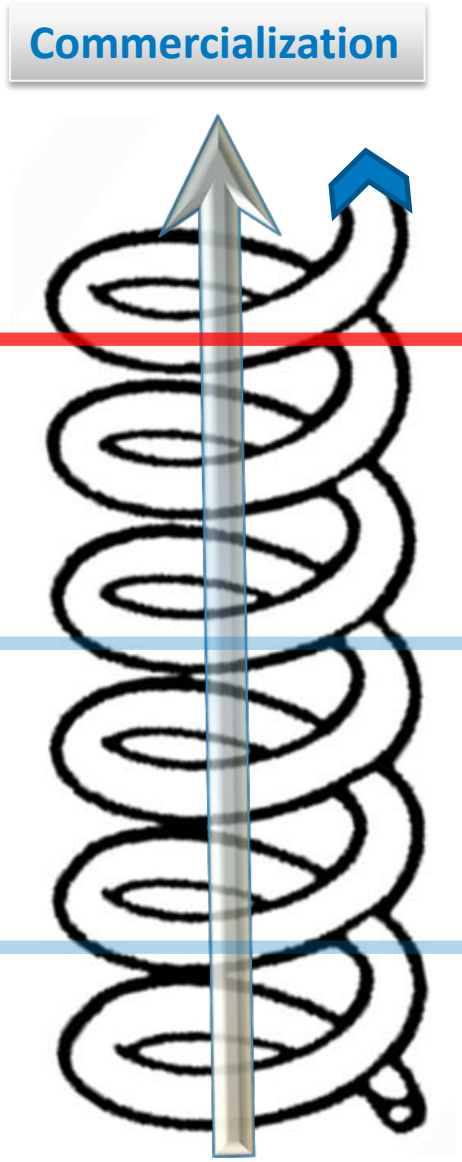


Figure 19: Wave LCOE Percentage Breakdown by Cost Centre Values at Current Stage of Deployment (Left) and the Commerical Target (Right) [Note: the area of the chart represents the LCOE].

Figures from International Energy Agency Ocean Energy Systems 2016 Report: "International Levelised Cost of Energy (LCOE) for Ocean Energy Technologies"

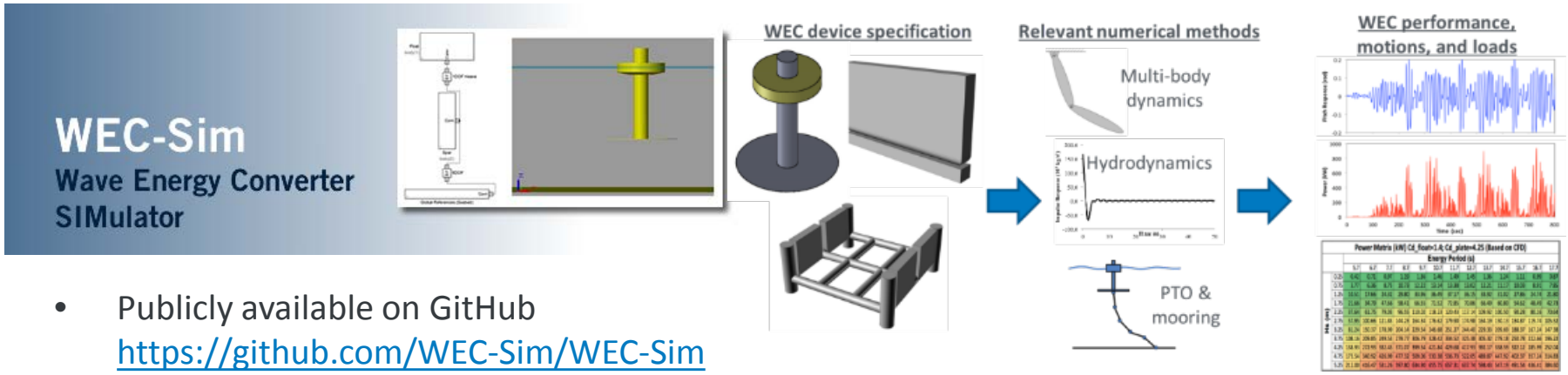
Advancement Through Effective Design and Development Iterations

(Design, Simulate, Build, Test, Validate, Refine, implement, maintain Repeat)



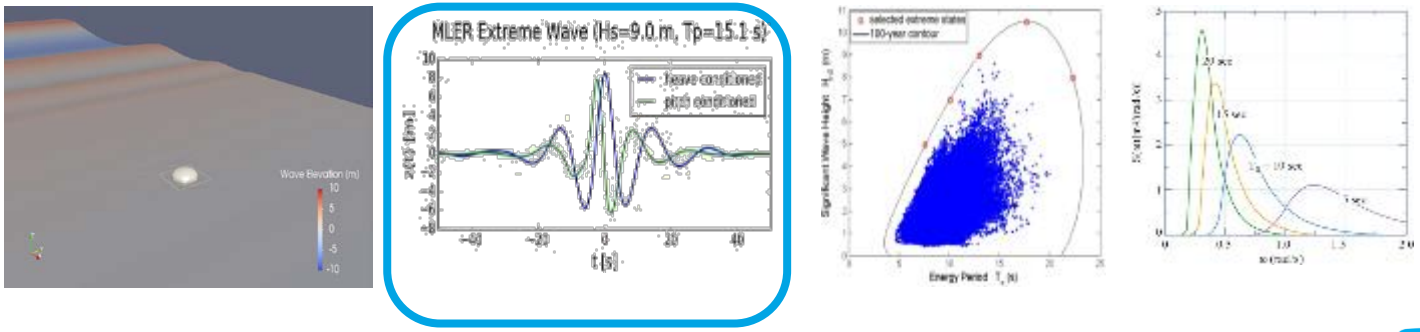
Key Elements	Phases
Reliability and Operations Supply Chain Market Development Value Engineering	**Commercial Readiness**
Certification and Standards Model Validation Power Quality Cost Validation and Optimization	**Open Water Validation and Assessment**
Proof of Concept Model Validation Cost Basis/Scalability Energy Production/Grid Response Reliability	**Controlled Validation and Assessment**
Requirement Definition Simulation TPL assessment	**Concept and Pathway Development**

WEC Design: Performance and survival



- Publicly available on GitHub
  https://github.com/WEC-Sim/WEC-Sim
- WEC-Sim Website and Documentation
  http://wec-sim.github.io/WEC-Sim/index.html

WEC Design Response Toolbox (WDRT) – Extreme Events



Figures from NREL and Sandia National Laboratories

Laboratory and Ocean Testing

Performance
- Verify and optimize power performance and quality
- Identify opportunities and approaches for improvement


Photo from Naval Surface Warfare Command

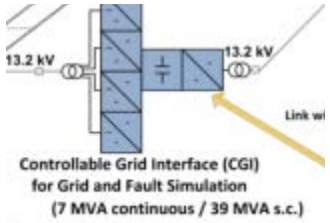
Reliability
- Assess and improve system and component reliability
- Identify areas for O&M focus and cost reduction


Photo by Scott Hughes, NREL

Capex
- Validate structural and dynamic models
- Refine designs and design margins


Photo by Mark McDade, NREL

Risk / Risk Perception
- Decrease real risks and risk perception
- Characterize grid and grid fault response
- Verify systems ready for deployment
- Device Certification testing

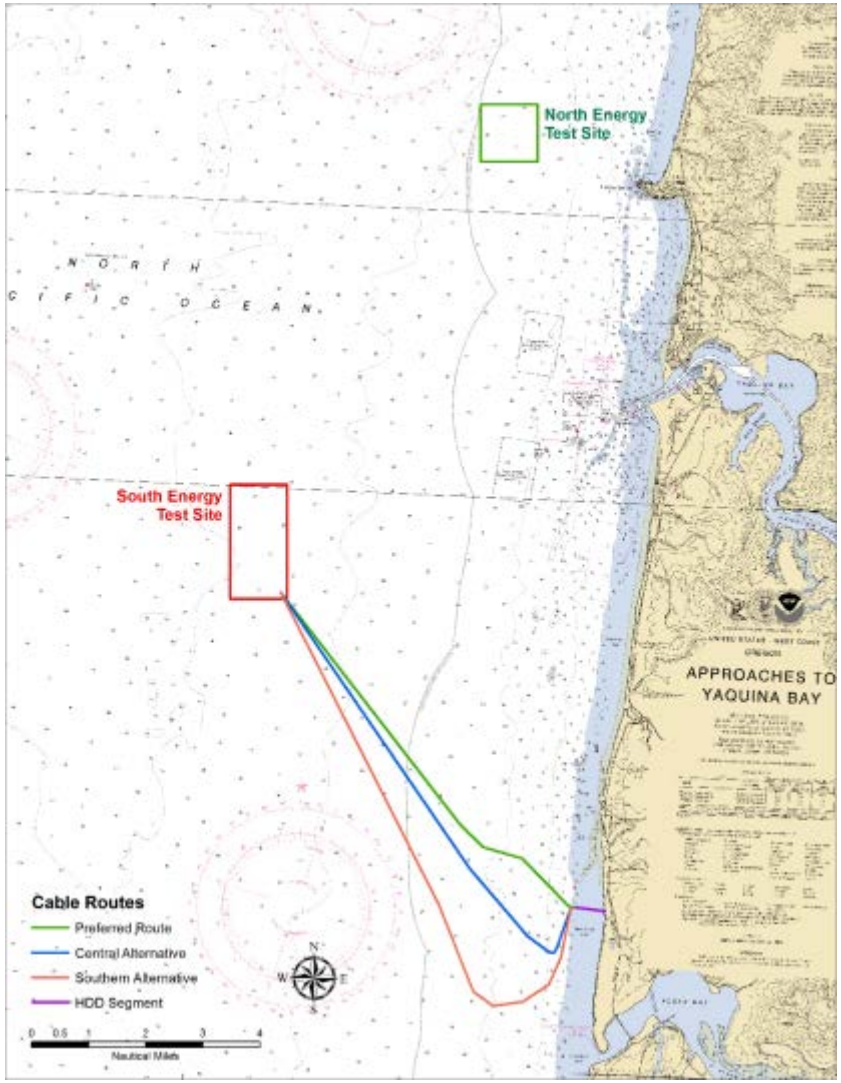


Controllable Grid Interface (CGI)
for Grid and Fault Simulation
(7 MVA continuous / 39 MVA s.c.)

Opportunity
- Project feasibility assessment
- Grid interconnection and value
- Market barrier and opportunity assessment


Photo by Eric Nelson, NREL

NNMREC and PMEC



NNMREC
Northwest National Marine Renewable Energy Center

Umbrella organization for wave, current, in river academic & scientific research

PMEC
Pacific Marine Energy Center

Umbrella organization for all marine renewable energy test facilities at partner institutions

Images from Oregon State University

NNMREC

U. S. Navy Wave Energy Test Site (WETS)/HINMREC

- Provides three grid connected berths (30/60/80 m depth; 1 to 2 km offshore)
- For technical evaluation and environmental impact assessment studies of in-water WEC devices

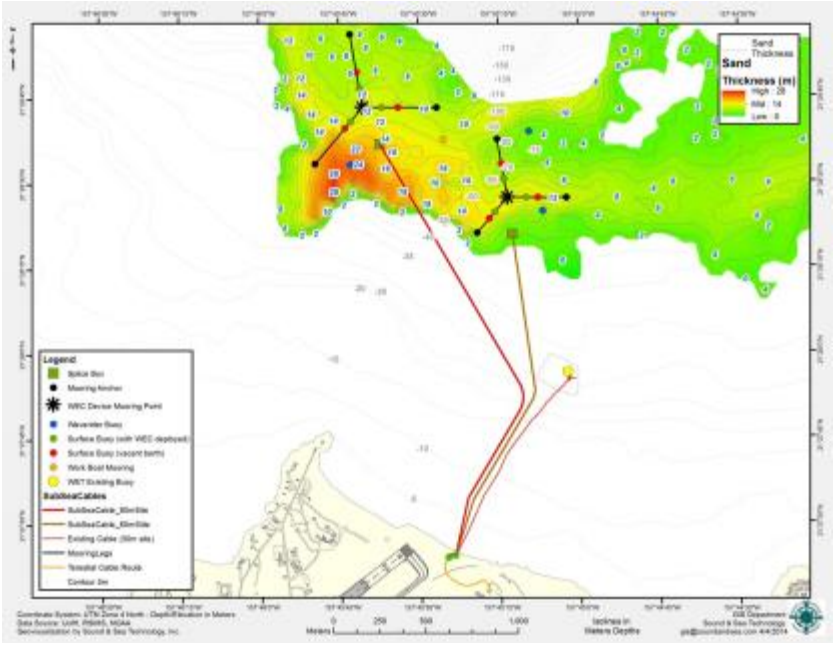
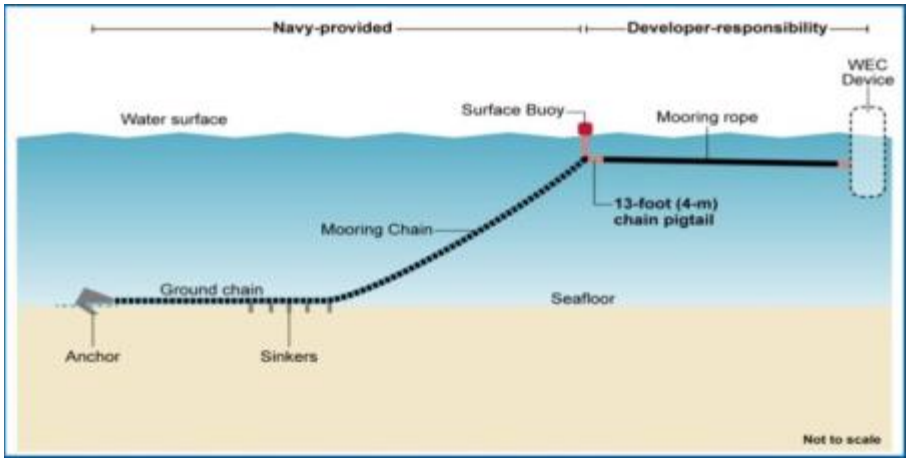


Figure from University of Hawai'I Manoa



1 of 3 mooring legs (80 m berth)
Figure from University of Hawai'I Manoa

Image from Columbia Power Technologies

UNIVERSITY of HAWAI'I MĀNOA

CalWave wave energy test site

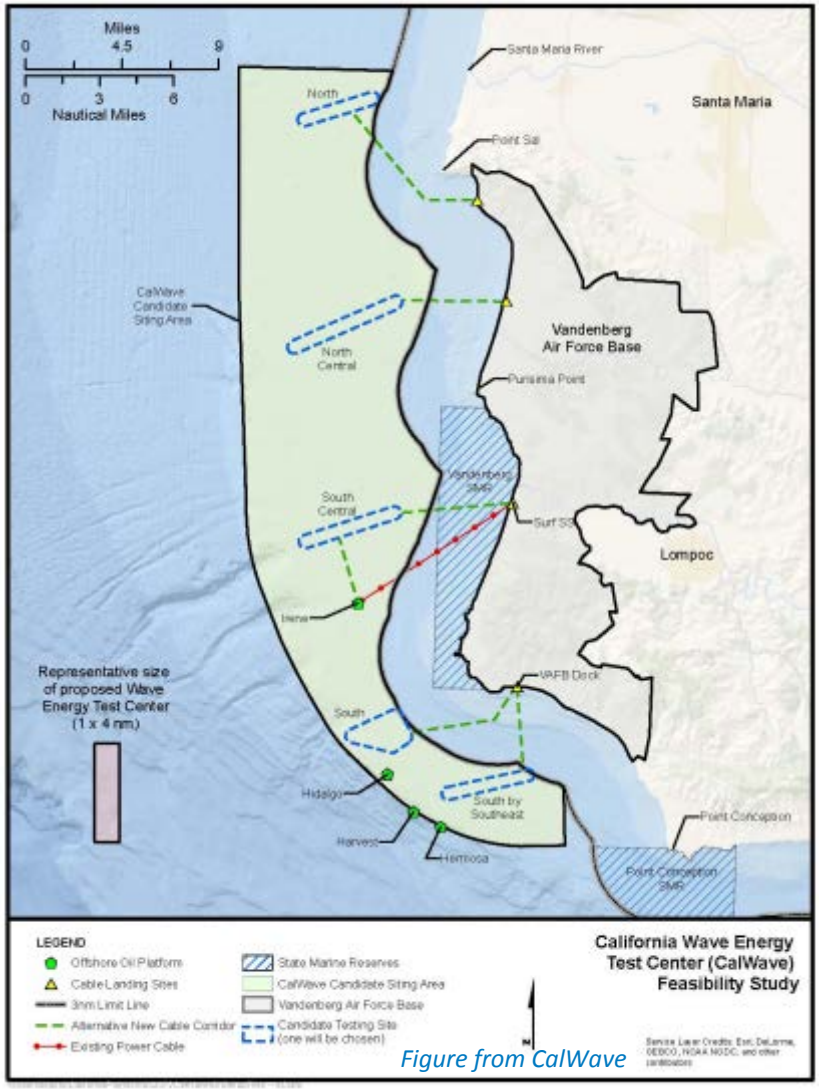


Figure from CalWave

Summary

- Global resource and opportunities in multiple markets
- International efforts to reduce risk and capitalize on resource
- Synergistic with existing CA industries and infrastructure
- Active R&D to increase performance and reliability and reduce costs
- Prototype deployments in U.S.

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