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Ocean Wave Energy Conversion – A Survey

Public domain photo by pdphotos.org.

Annette Muetze und Jennifer Vining

Outline

- Ocean Energy Resources
- Wave Energy – Some Calculations
- Classification of Wave Energy Converters
- Open Questions
  - A Lot of Room for Research!
- Conclusions

Hydropower Plants – Well-Known

Public domain photo (in the US, work of the US Federal Government), available at www.wikipedia.com.

Aerial view of Saint Anthony Falls with the upper dam (there is also a lower dam)

Public domain photo available at www.wikipedia.com.

Undershot water wheels on the Orontes River in Hama, Syria.

But the ocean itself is a large energy source!

Ocean Energy Resources

- Energy transfer: Sun → Wind → Water

- Marine currents ⇐ Already
- Tidal currents ⇐ limited
- Geothermal winds commercial
- Waves ⇐ interest

Marine and Tidal Currents

- Energy from marine and tidal currents

1. Marine currents
   - E.g. Gulf Stream
   - Uni-directional
2. Tidal currents
   - Half-day/ daily/ 14-day cycles
   - Bi-directional

- Prototypes have been realized
- Technology similar to hydroelectric (some models – "underwater wind turbines")

Marine and Tidal Currents

- Energy from marine and tidal currents
- Estimated 5 TW world-wide
  - On the scale of the world's power consumption

Source: R. Bound, "Status and Research and Development Priorities Wave and Marine Current Energy," UK Dep. Of Trade and Industry, 2003.

- Easy to predict, because it is influenced by the rotation of the earth.

Ocean Energy Resources

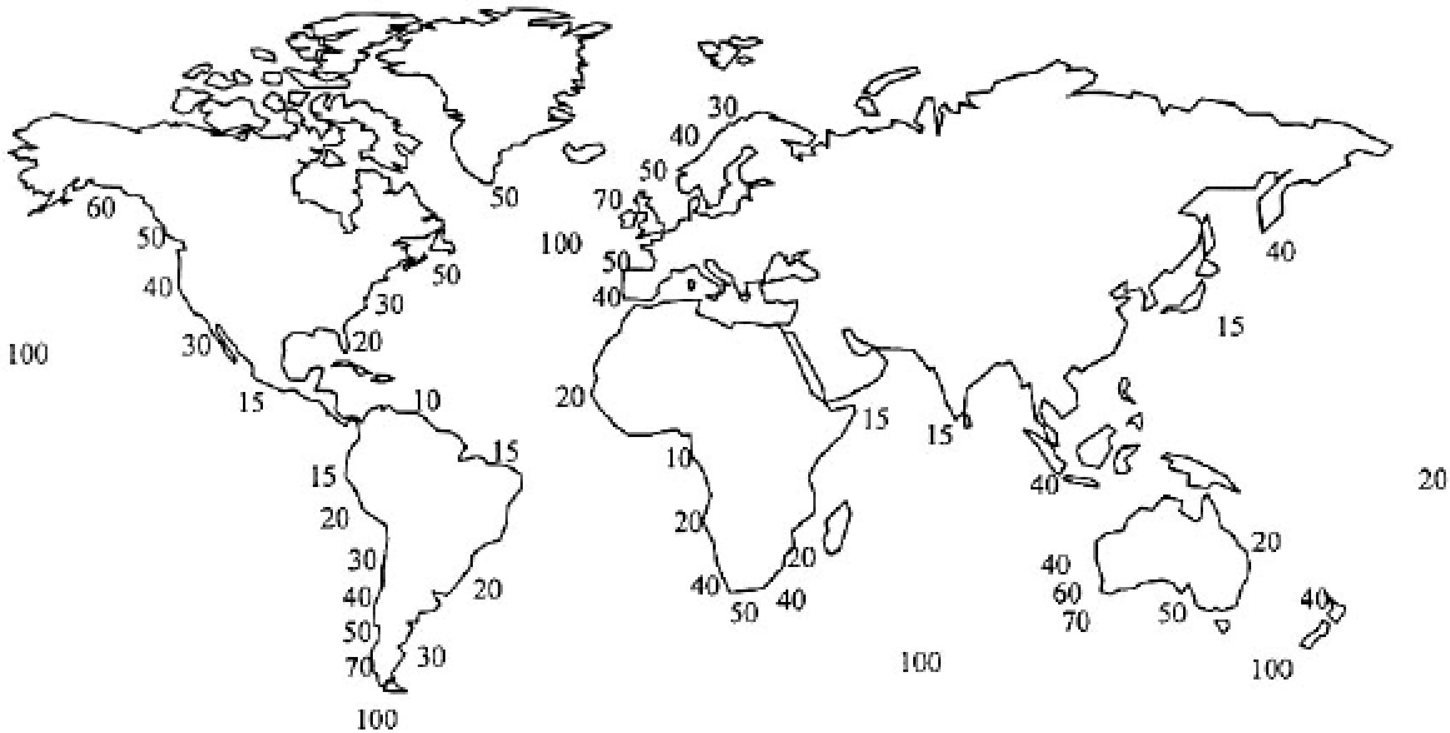
- Wave energy facts
  - Wave energy provides "15-20 times more available energy per square meter than either wind or solar."

Source: "Electric Power from Waves," Wavemill Energy Corp.

  - Regular source of power that can be predicted days in advance.

Public domain photo by pdphotos.org.

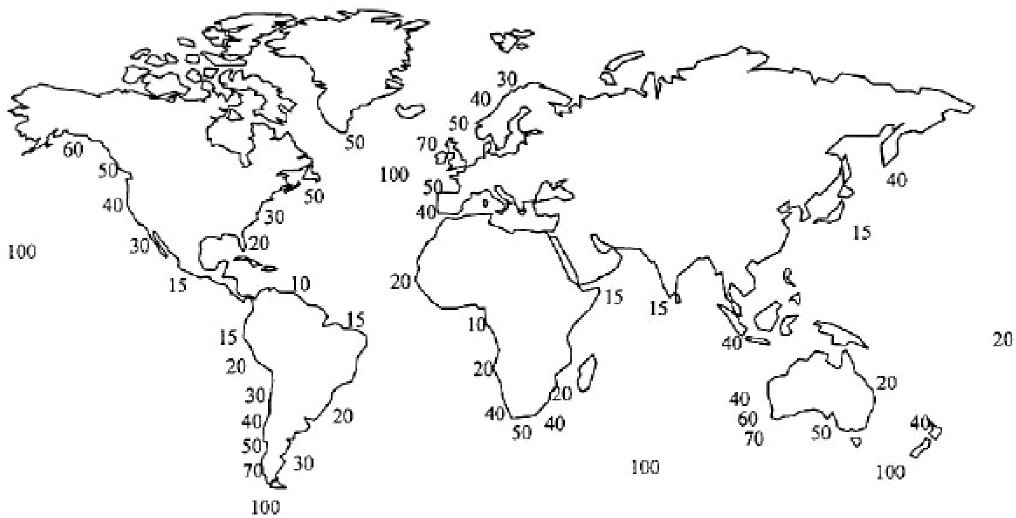
Wave Power Levels (kW/m wave crest)



Source: T.W. Thorpe, ETSU, Nov. 1999.

- Note: West-to-east winds cause greater wave energy on western edge of continents.

Ocean Energy Resources



Source: T.W. Thorpe, ETSU, Nov. 1999.

- Ocean Currents
  - 5 TW
- Waves
  - 8,000 - 80,000 TWh/yr
  - 1 - 10 TW

[R. Boud, DTI Report # FES-R-132, UK, 2003.]

  - 10 - 50 kW/m per average wave crest

⇒ Definition of the "Wave climate"

Commercialization

- Plans for commercial installations all over the world (Spain, France, New Jersey, New York, etc.)

"The footprint of a 100 MW conventional power plant superstructure, including surrounding grounds, fuel unloading areas, waste settling ponds, and additional facilities can require up to 2 square miles of valuable real estate. A comparable OPT power plant would occupy less than 1 square mile of unused ocean surface out of sight from the shore."

Source: "The Power of Waves. The Future of Energy." *Ocean Power Technologies*, http://www.oceanpowertechnologies.com.

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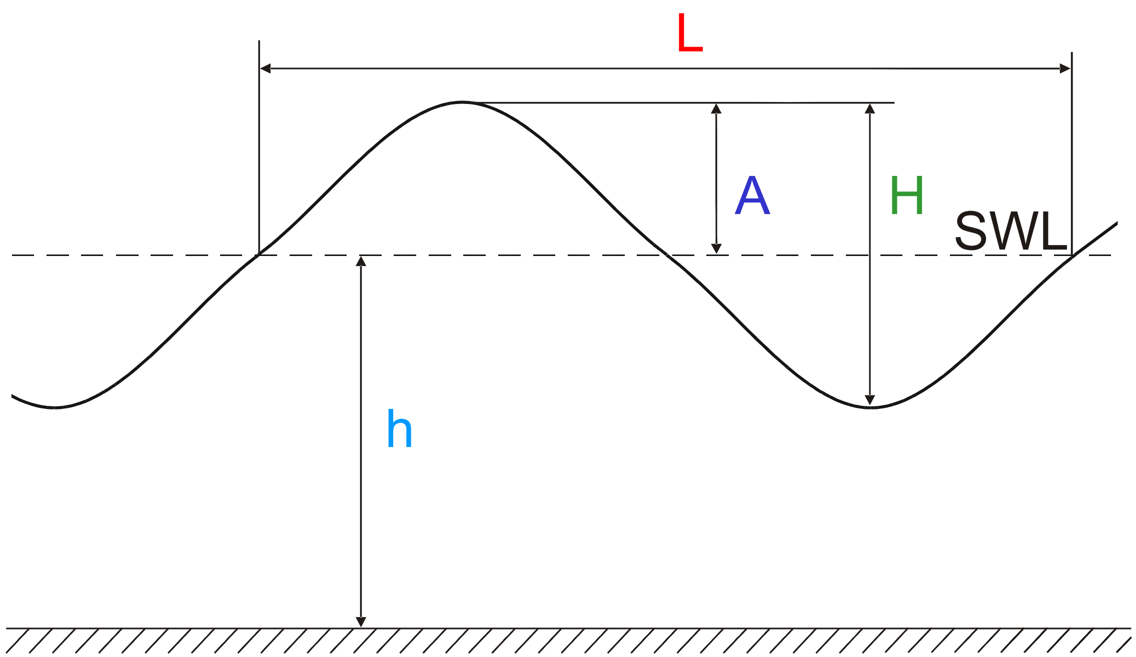
"The utilization factor for wave power – the ratio of yearly energy production to the installed power of the equipment – is typically 2 times higher than that of wind power. That is whereas for example a wind power plant only delivers energy corresponding to full power during 25% of the time (i.e. 2,190 h out of the 8,760 h per year) a wave power plant is expected to deliver 50% (4,380 h/year)."

Source: „Bringing Ocean Power to the World," *Seabased Energy AB*, http://www.seabased.com.

Wave Nomenclature



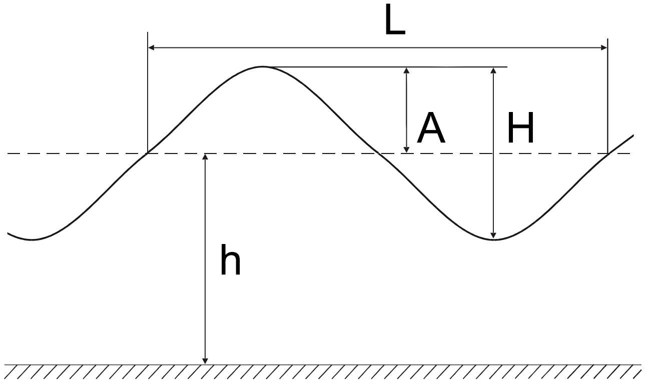
Based on “Archimedes Wave Swing: Theory,” Ocean Power Technologies, http://www.waveswing.com.

SWL	mean seawater level (surface)	λ (or L)	wavelength [m]
h	depth below SWL [m]	A	wave amplitude [m]
C	celerity (wave front velocity)	H	wave height [m]

Wave Energy and Power Density Calculations

- Energy density
  - mean energy flux crossing a vertical plane parallel to a wave's crest

$$E_{density} = \rho_{water} g H^2/8 = \rho_{water} g A^2/2$$



Based on "Archimedes Wave Swing: Theory," Ocean Power Technologies, http://www.waveswing.com.

ρ_{water} seawater density (1000 kg/m^3)

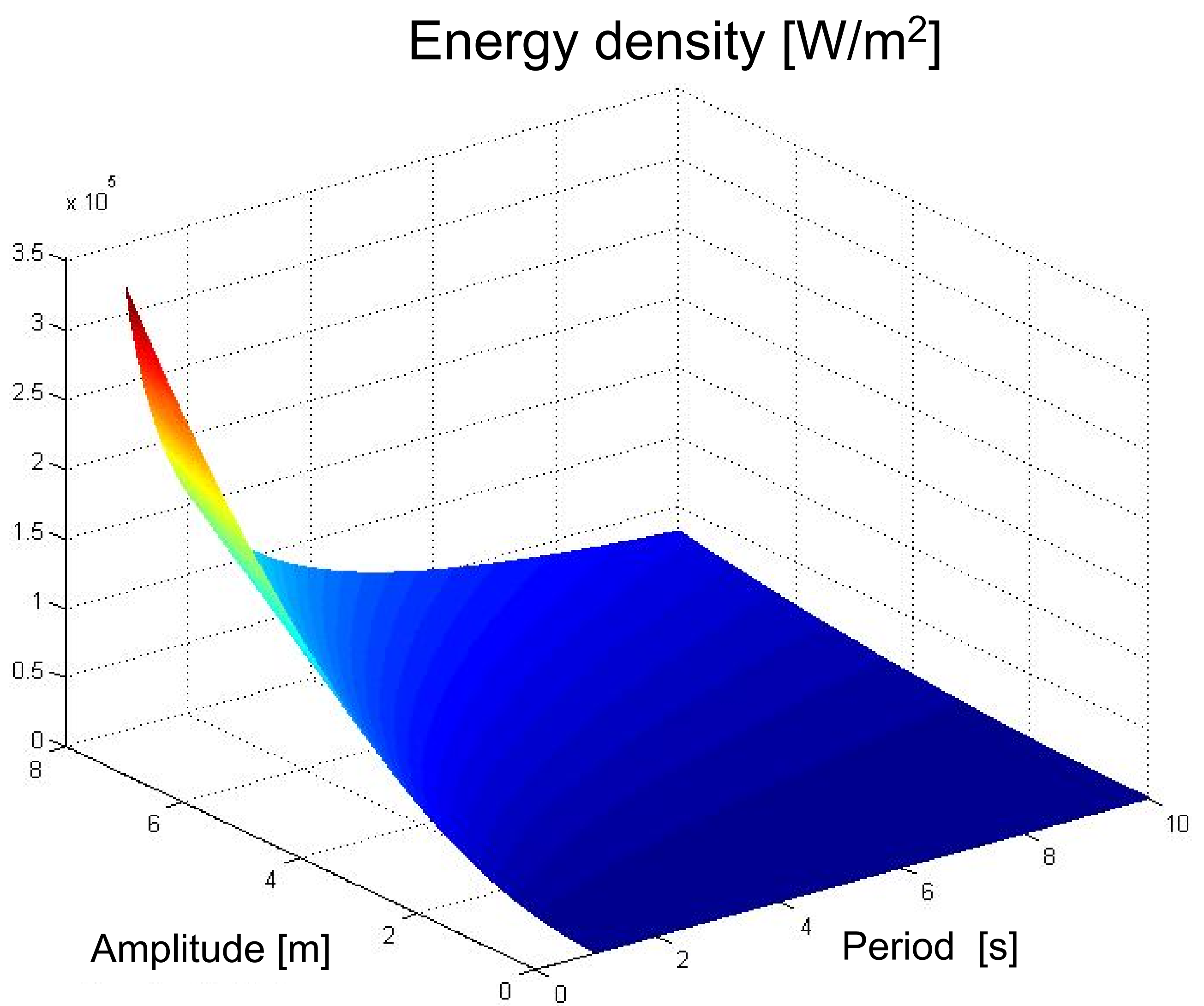
g gravitational constant (9.81 m/s^2)

- Power density
  - energy per wave period

$$P_{density} = E_{density}/T = \rho_{water} g H^2/(8T) = \rho_{water} g A^2/(2T)$$

T period time [s]

Graph of Wave Energy Density



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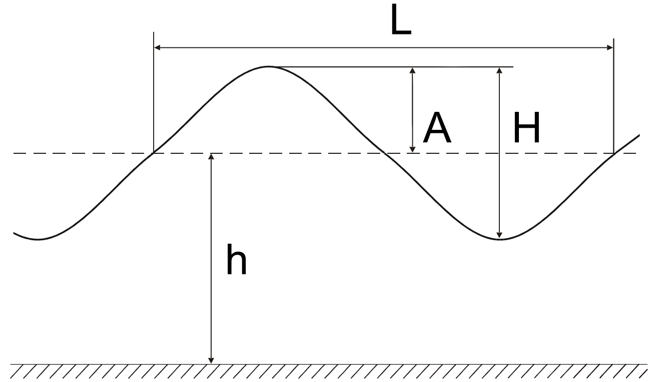
Power per Meter Wave-Front Calculation

- kW/m

  = typical unit of measure for wave power

- Power per wave-front

  = energy density · wave-front velocity

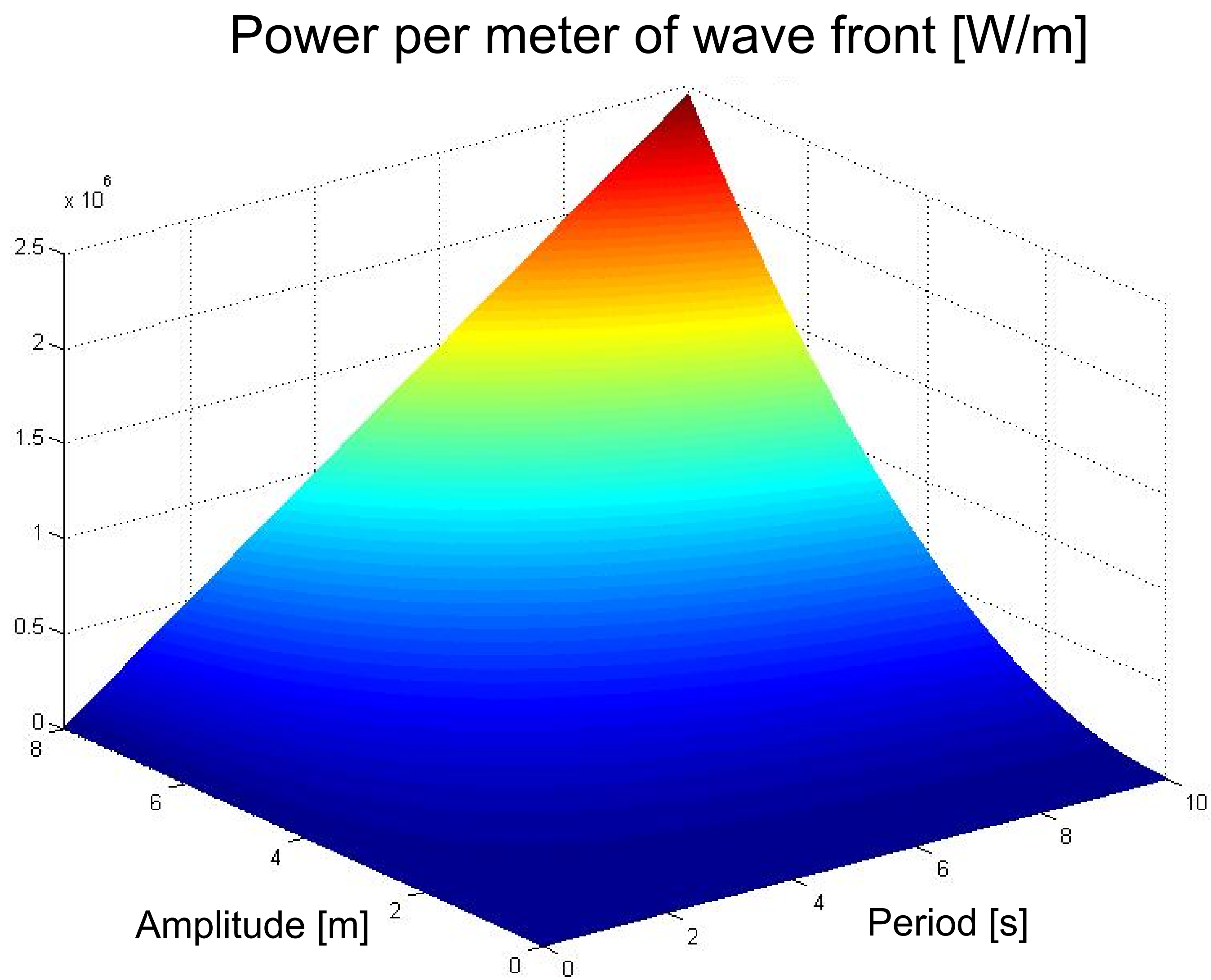


Based on "Archimedes Wave Swing: Theory," Ocean Power Technologies, http://www.waveswing.com.

$$P_{\text{wavefront}} = C \cdot E_{\text{density}}$$

$$= \rho_{\text{water}} g^2 H^2/(16\omega) = \rho_{\text{water}} g^2 A^2/(4\omega)$$

Graph of Wave Power



Influence of Water Depth on Wave Energy

- Underwater wave energy converters…?
  - Relationship between wave energy and water depth?

- Generally: Wave energy decreases exponentially with $-2\pi d/\lambda$.

$$E(d) = E(d{=}SWL) \cdot e^{-2\pi d/\lambda}$$

d depth, distance to SWL [m] (total depth at least $\lambda/2$)

⇒ Enough formulas for today…

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WEC Classifications

Ocean Wave Energy Converters (WECs)	
Turbine-type	***Buoy-type or "Point Absorber"***
Oscillating Water Column (OWC)	Tube type
Overtopping Wave Energy Converter	Float type

↑ Received research attention early on

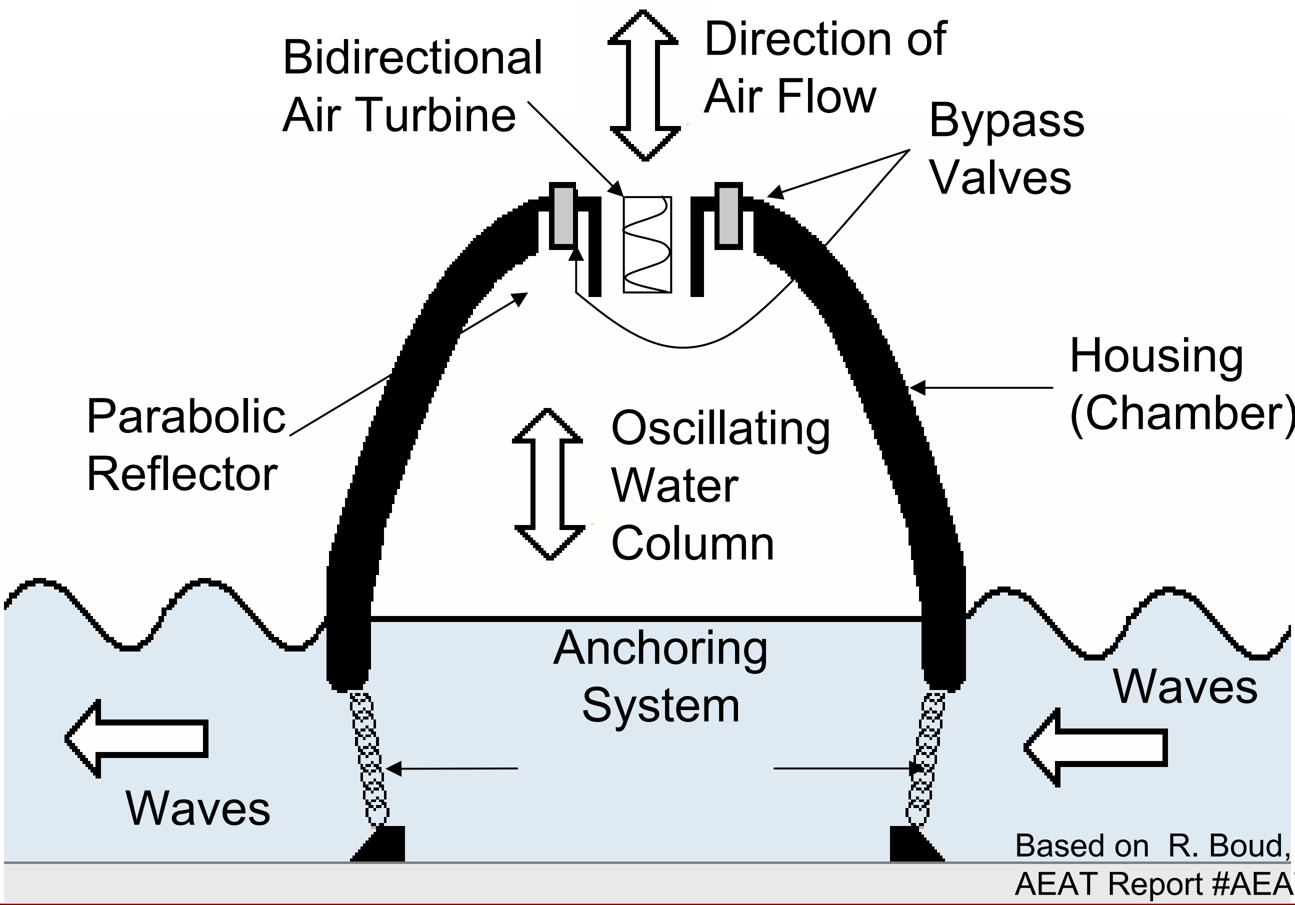
↑ Newer idea

Other forms worthy of notice: Pelamis (Ocean Power Delivery Ltd.)

Note: Ocean current converters are not discussed due to their relatively mature technology which resembles hydroelectric.

Oscillating Water Column (OWC)

- Operates much like a wind turbine via the principle of wave induced air pressurization.

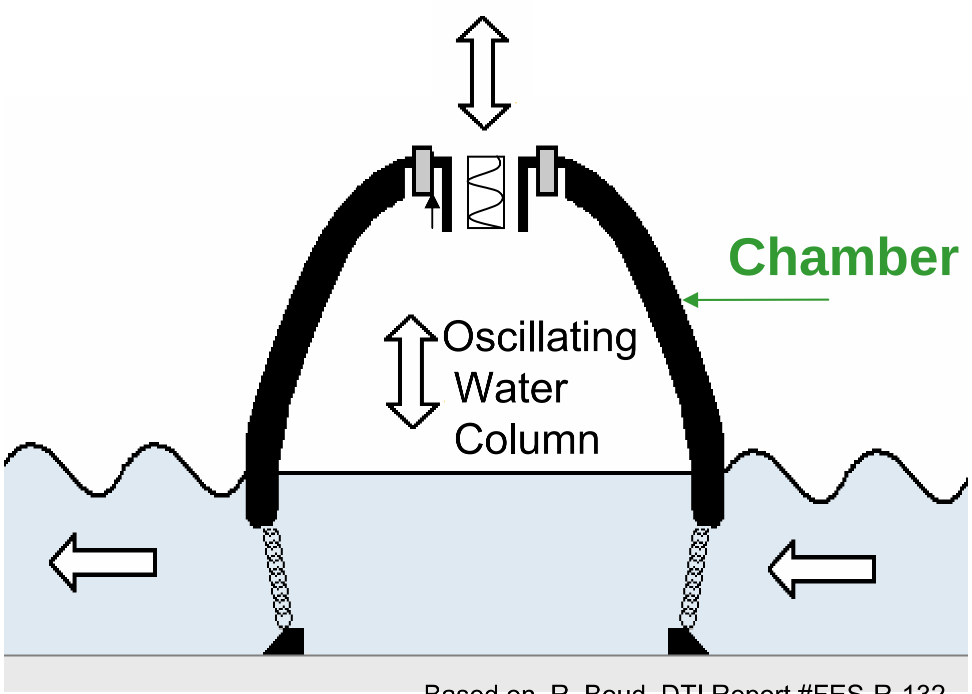


Based on R. Boud, DTI Report #FES-R-132, AEAT Report #AEAT/ENV/1054, UK, 2003.

OWC Air Chamber Design

(selected)

- Air chamber
  - Wave resonance within the chamber can cause net zero passage of air through the turbine.
  - Must be designed with the wave period, height, and length character-istics of local wave climate in mind.
  - Must be conducive to air-flow through turbine.



Based on R. Boud, DTI Report #FES-R-132, AEAT Report #AEAT/ENV/1054, UK, 2003.

OWC Placement

(selected)

- Placement
  - Near-shore: Eye sores? Noise? Public acceptance?
  - Shoreline: generally greater wave energy, but installation and maintenance costs…

(Lacking available wave-energy pictures – analogous:)

Danish wind turbines near Copenhagen

Fixed and Slack Mooring

(selected)

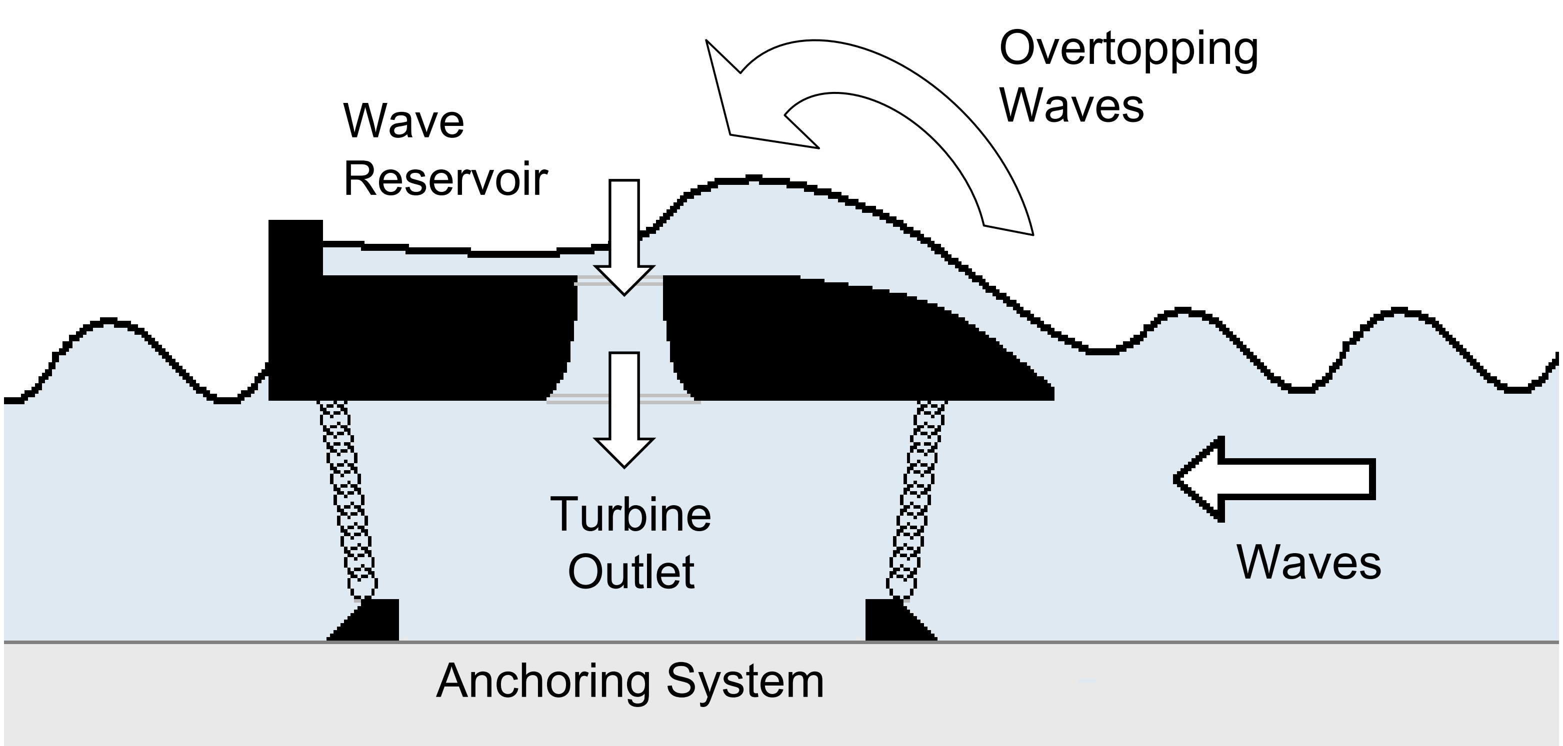
- Fixed mooring
  - Analogue to off-shore wind-turbines
  - Can better maintain its the position

    → higher resistance to incoming waves

    → higher energy production
- Slack mooring
  - Can react to change of SWL (i.e. tides)
  - Flexible in rough seas (might damage fixedly moored devices)
  - Lower installation costs

Overtopping WEC

- Works much like a hydroelectric dam



Based on "Marine Energy Challenge," *The Carbon Trust*, www.thecarbontrust.co.uk.

Recap: WEC Classifications

Ocean Wave Energy Converters (WECs)	
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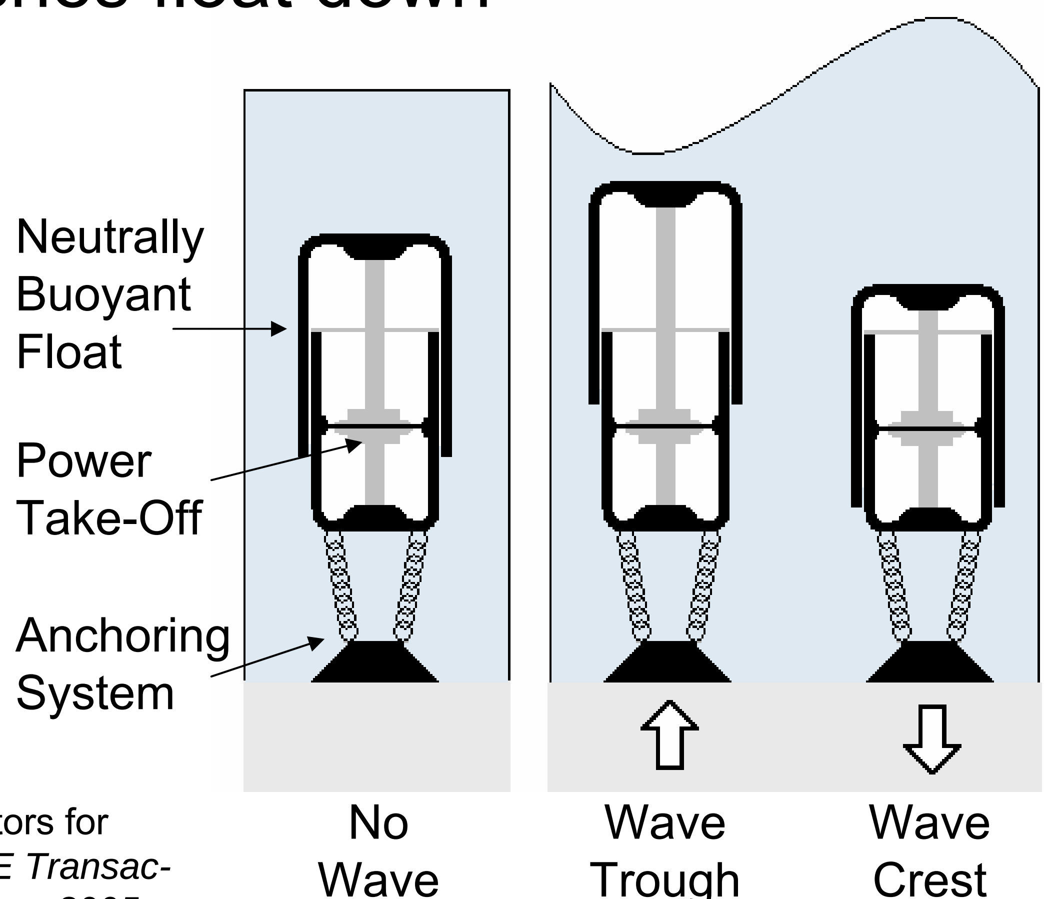
Point Absorber – Float Type

- Wave Crest
  - Water weight pushes float down
- Wave Trough
  - Float rises

Below surface point absorber

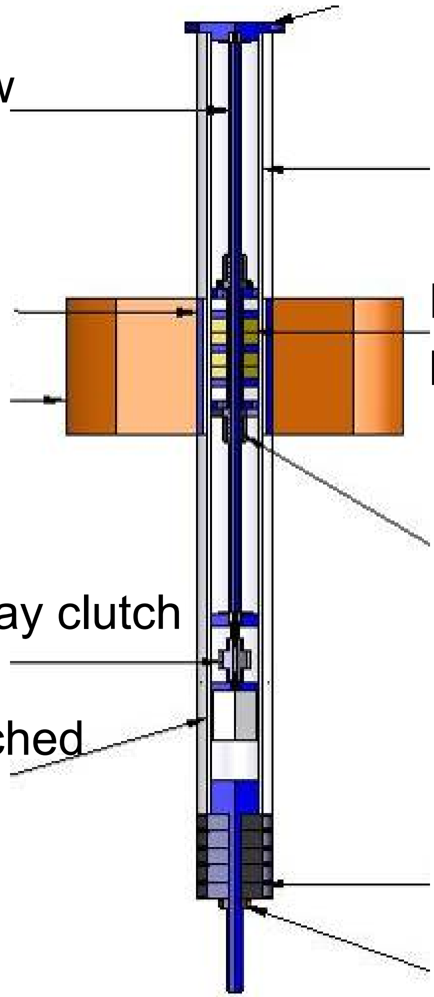


Based on "Conventional and TFPM Generators for Direct-Drive Wave Energy Conversion," *IEEE Transactions on Energy Conversion*, vol.20, no. 2, June 2005.

Point Absorber – Float Type

- Float type
  - Float position
    - On ocean surface (positively buoyant)
    - Below ocean surface (neutrally buoyant)
  - Power take-off
    - *Linear generator,* piston directly coupled to linear generator
    - *Hydraulics:* piston pumps hydraulic fluid
    - *Hose pump*
    - *Contact-less force transmission*

Contact-Less Force Transmission System (OSU)



(also: current research!)

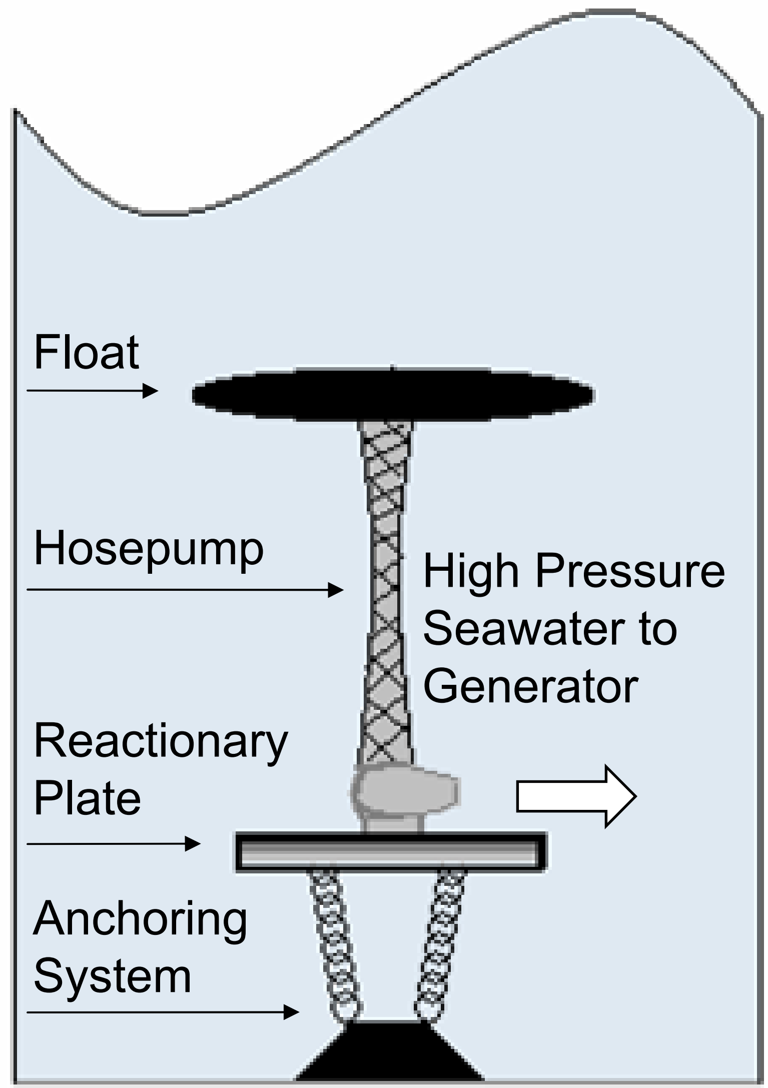
No mechanical link between float and power take-off.

Magnetic field between the piston's permanent magnets and the iron cylinder attached to the float acts as the intermediary, creating a reluctance force.

Source: A.von Jouanne, used with permission. Published in: E. Agamloh, A. Wallace, and A. von Jouanne, „A Novel Direct-Drive OceanWave Energy Extraction Concept with Contact-less Force Transmission System", *American Institute of Aeronautics and Astronautics*, 44th AAIA Areospace Science Meeting and Exhibit , Reno, Nevada, January 9-12, 2006.

Point Absorber – Hose Pump

- Similar to hydraulic system
- Float moves relative to reaction plate
  - Hose stretches, pulls in seawater
  - Hose constricts, pushes pressurized seawater to hydrau-lic generator



Based on R. Boud, DTI Report #FES-R-132, AEAT Report #AEAT/ENV/1054, UK, 2003.

Point Absorber – Tube Type

- Tube type
  - Like float type, except one or both ends of "tube" are open – vertically submerged, neutrally buoyant hollow tube
  - Waves cause pressure difference between ends of tube, inducing sea water to flow
  - Power take-off: piston
    - *Linear generator,* piston directly coupled to linear generator
    - *Hydraulics,* piston pumps hydraulic fluid

Important Design Parameters

OWC	Point Absorber
Wave height, length, and period	Wave height, length, and period
Chamber dimensions	Total mean water depth
By-pass valve control	Depth of device below water
	Length and diameter of float, tube, and/or pump
	Stroke length

More Pictures

Many more pictures (and other information!) can be found on the internet! - Some examples:

- Ocean Power Technology http://www.oceanpowertechnologies.com/
- Ocean Power Delivery Ltd http://www.oceanpd.com/default.html
- AcquaEnergy Group Ltd. http://www.aquaenergygroup.com/
- O.H. Hinsdale Wave Research Laboratory at OSU (HWRL) http://wave.oregonstate.edu

  and
- Motor Systems Resource Facility at OSU (MSRF) http://eecs.oregonstate.edu/msrf/

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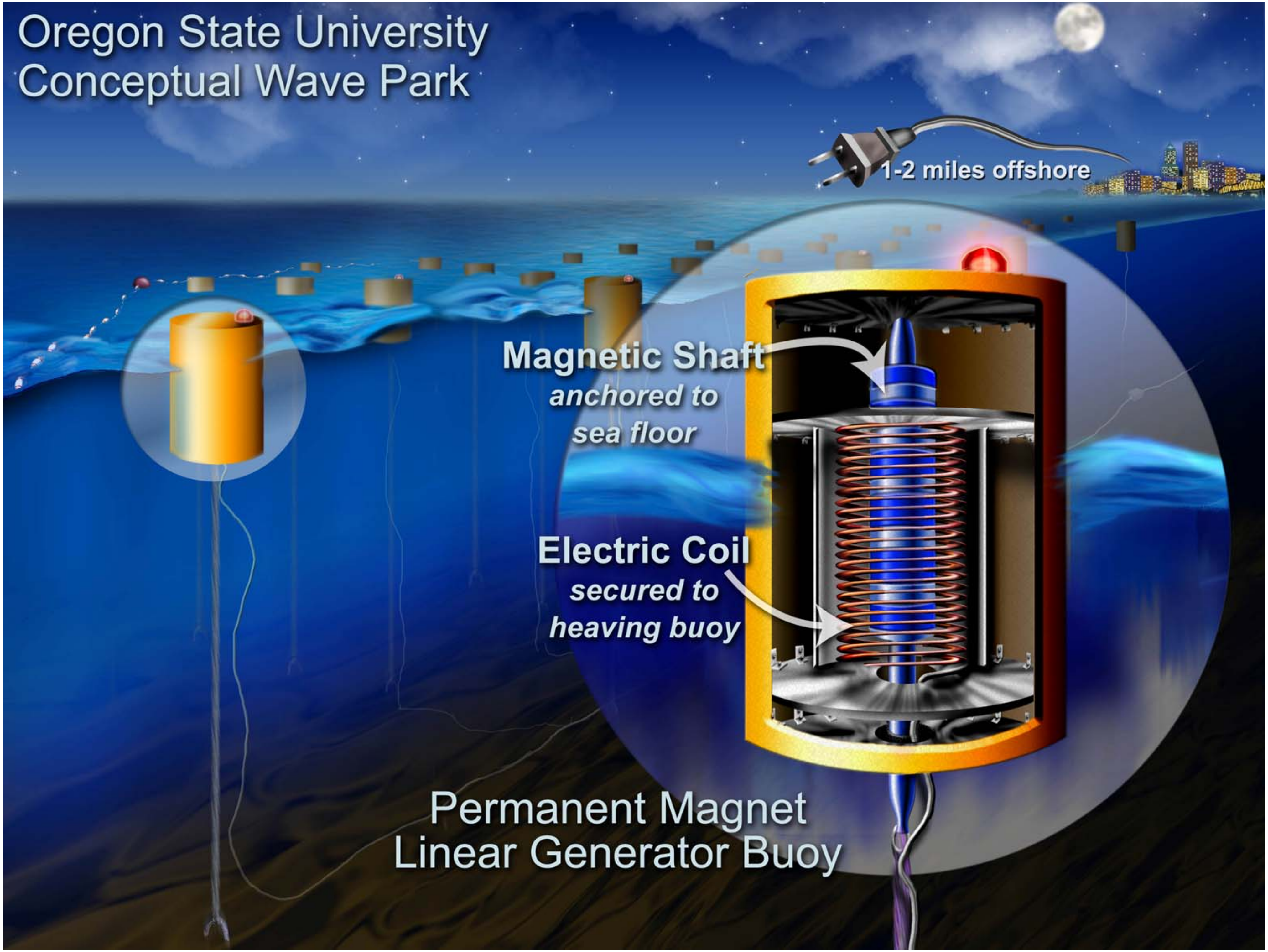
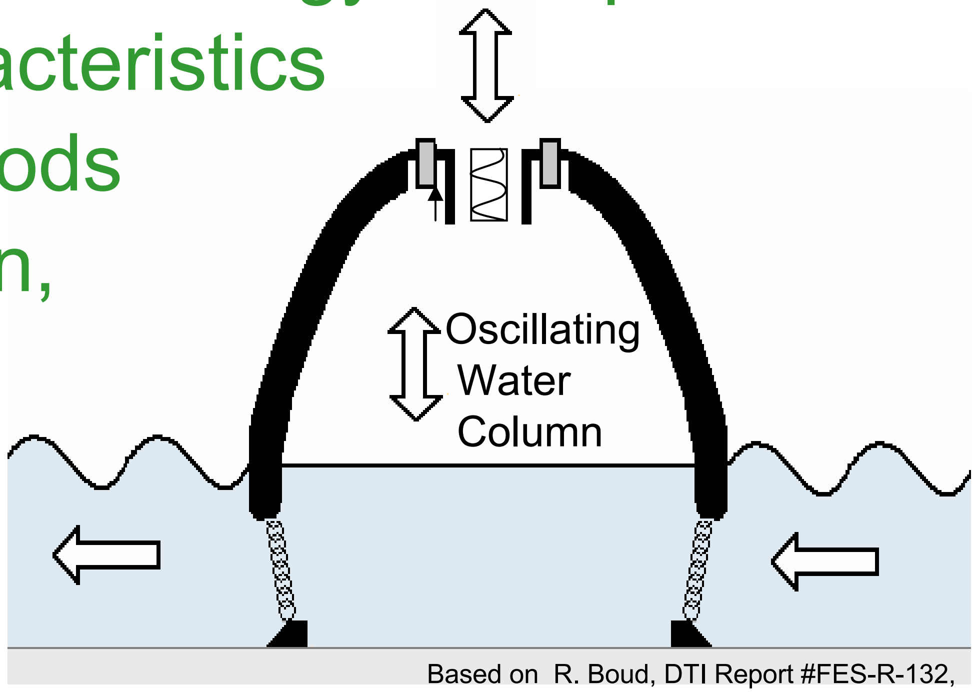

Oregon State University
Conceptual Wave Park
1-2 miles offshore
Magnetic Shaft
anchored to
sea floor
Electric Coil
secured to
heaving buoy
Permanent Magnet
Linear Generator Buoy

Common Research Topics

- OWC
  - Air pressure and flow control (bypass valve)
  - Turbine designs
  - Turbine control of wave energy absorption
  - Hydrodynamic characteristics
  - Overall design methods
  - Moorings, installation, and foundation
  - System resonance



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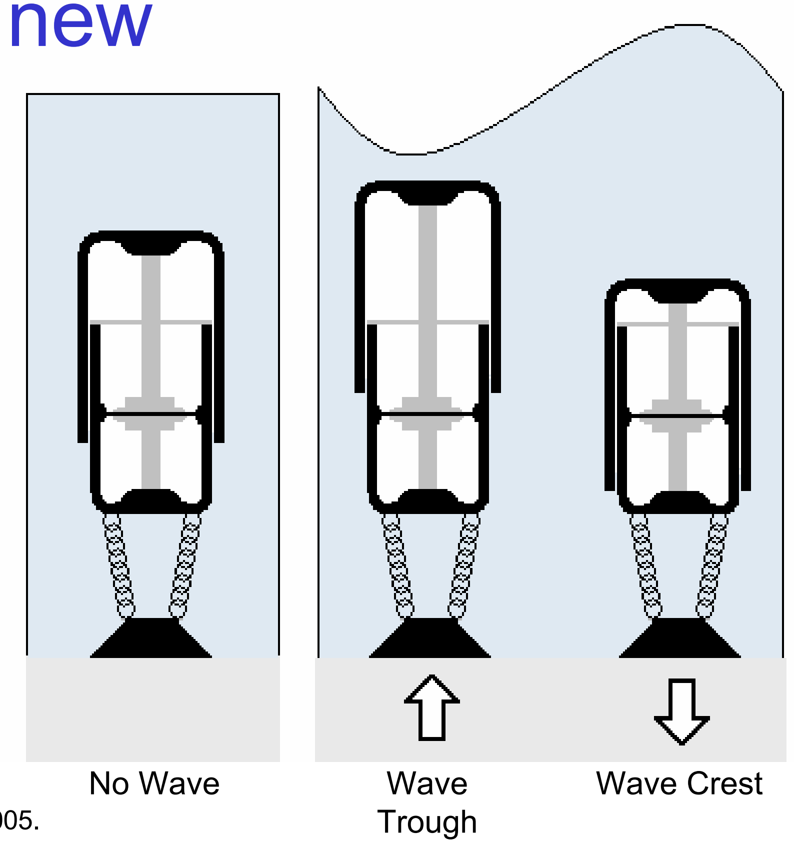
Common Research Topics

- Point Absorber
  - Control techniques
  - Turbine design including new power take-off methods
  - Moorings, installation, and foundation



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… A Lot of Room for Research!

- High-pressure underwater electric cables
- Purpose-designed inverters
- Wave energy converter dynamic response
- Mechanical
  - Air pressure and flow control (bypass valve)
  - Turbine designs
  - Turbine control of wave energy absorption
  - Hydrodynamic characteristics
  - Overall design methods →→→

… A Lot of Room for Research!

- Mechanical cont.
  - …
  - Moorings, installation, and foundation
  - System resonance, …
- Electrical
  - Direct power take-off methods
  - Power conversion
  - Power controls
  - Power transmission
  - Electrical reliability
  - Electrical maintenance
  - Grid connection requirements, …

… A Lot of Room for Research!

- Other areas
  - Weather forecasting for real-time wave behavior
  - Navigating around devices
  - Standardized testing of devices
  - Cost effective waterproofing, corrosion resistant materials, offshore access, …
- Environmental problem areas
  - Animals
  - Coast lines
  - Fauna and seabed
  - Visual impact
  - Pollution,…

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Overall Comparison of Major Renewable Energy Sources

THE UNIVERSITY of WISCONSIN MADISON

Energy Type	Predictability	Energy Density	Potential Sites
Wave	Predictable at most sites	High	70% of Earth is Ocean!
Wind	Fairly unpredictable	Low	Limited to areas with high average wind speed
Photovoltaic (Solar)	Fairly unpredictable	Low	Limited to sunny areas

Conclusion

- Potential of wave energy as an up-and-coming energy source?
- Turbine-/ Point-absorber type, sub-groups
- Also: Many open questions on the road towards commercialization…
- Transfer of knowledge gained in other fields?
- Questions?