

### Ocean Wave Energy Conversion – A Survey





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#### 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  $\rightarrow$  Wind  $\rightarrow$  Water
- Marine currents
- Tidal currents
- Geothermal winds
- Waves

- $\leftarrow$  Already
- $\leftarrow$  limited
  - commercial
- *⇐* 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.



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#### 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.

#### ⇒ Definition of the "Wave climate"

- 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



# 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.

SWLmean seawater level (surface)λ (or L)wavelength [m]hdepth below SWL [m]Awave amplitude [m]Ccelerity (wave front velocity)Hwave 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.

• Power density

- energy per wave period

 $\rho_{water}$  seawater density (1000 kg/m<sup>3</sup>) g gravitational constant (9.81 m/s<sup>2</sup>)

$$P_{density} = E_{density}/T = \rho_{water}gH^2/(8T) = \rho_{water}gA^2/(2T)$$

T period time [s]



# **Graph of Wave Energy Density**







# Power per Meter Wave-Front Calculation



• kW/m

= typical unit of measurefor wave power

Power per wave-front
 = energy density
 · wave-front velocity



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

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

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



#### **Graph of Wave Power**





![](_page_17_Picture_0.jpeg)

# Influence of Water Depth on Wave Energy

![](_page_17_Picture_2.jpeg)

- 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  $\lambda/2$ )

 $\Rightarrow$  Enough formulas for today...

![](_page_18_Picture_0.jpeg)

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![](_page_18_Picture_2.jpeg)

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![](_page_19_Picture_0.jpeg)

# **WEC Classifications**

![](_page_19_Picture_2.jpeg)

| Ocean Wave Energy Converters (WECs)          |                                  |  |  |
|--|----------------------------------|--|--|
| Turbine-type                                 | Buoy-type<br>or "Point Absorber" |  |  |
| Oscillating Water Column (OWC)               | Tube type                        |  |  |
| Overtopping Wave Energy<br>Converter         | Float type                       |  |  |
| ↑<br>Received research<br>attention early on | ↑<br>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.

Power Area and CEME Seminar at UIUC, October 2, 2006

![](_page_20_Picture_0.jpeg)

# Oscillating Water Column (OWC)

![](_page_20_Picture_2.jpeg)

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

![](_page_20_Figure_4.jpeg)

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![](_page_21_Picture_0.jpeg)

# **OWC Air Chamber Design**

![](_page_21_Picture_2.jpeg)

#### • 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 characteristics of local wave climate in mind.
- Must be conducive to air-flow through turbine.

![](_page_21_Figure_7.jpeg)

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

![](_page_22_Picture_0.jpeg)

# **OWC Placement**

![](_page_22_Picture_2.jpeg)

• 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

![](_page_22_Picture_7.jpeg)

Source: Wikipedia Commons, licensed under the Creative Commons Share Alike License, available at www.wikipedia.com

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![](_page_23_Picture_0.jpeg)

# **Fixed and Slack Mooring**

![](_page_23_Picture_2.jpeg)

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

 $\rightarrow$  higher resistance to incoming waves

 $\rightarrow$  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

![](_page_24_Picture_0.jpeg)

# **Overtopping WEC**

![](_page_24_Picture_2.jpeg)

• Works much like a hydroelectric dam

![](_page_24_Figure_4.jpeg)

![](_page_25_Picture_0.jpeg)

![](_page_25_Picture_1.jpeg)

# **Recap: WEC Classifications**

| Ocean Wave Energy Converters (WECs)          |                                  |  |  |
|--|----------------------------------|--|--|
| Turbine-type                                 | Buoy-type<br>or "Point Absorber" |  |  |
| Oscillating Water Column (OWC)               | Tube type                        |  |  |
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![](_page_26_Picture_0.jpeg)

![](_page_26_Picture_1.jpeg)

# Point Absorber – Float Type

Wave Crest

Water weight pushes float down

![](_page_26_Figure_5.jpeg)

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![](_page_27_Picture_0.jpeg)

![](_page_27_Picture_1.jpeg)

# **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

![](_page_28_Picture_0.jpeg)

# Contact-Less Force Transmission System (OSU)

![](_page_28_Picture_2.jpeg)

![](_page_28_Figure_3.jpeg)

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 Contactless Force Transmission System", *American Institute of Aeronautics and Astronautics*, 44<sup>th</sup> AAIA Areospace Science Meeting and Exhibit , Reno, Nevada, January 9-12, 2006.

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![](_page_29_Picture_0.jpeg)

# Point Absorber – Hose Pump

![](_page_29_Picture_2.jpeg)

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

![](_page_29_Figure_7.jpeg)

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

![](_page_30_Picture_0.jpeg)

![](_page_30_Picture_1.jpeg)

# **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

![](_page_31_Picture_0.jpeg)

![](_page_31_Picture_1.jpeg)

# **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,<br>and/or pump |  |
|                                 | Stroke length                                      |  |

![](_page_32_Picture_0.jpeg)

#### **More Pictures**

![](_page_32_Picture_2.jpeg)

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. <a href="http://www.aquaenergygroup.com/">http://www.aquaenergygroup.com/</a>
- 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/

![](_page_33_Picture_0.jpeg)

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![](_page_33_Picture_2.jpeg)

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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

![](_page_35_Picture_0.jpeg)

![](_page_35_Picture_1.jpeg)

# **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

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

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Oscillating

Water Column

![](_page_36_Picture_0.jpeg)

![](_page_36_Picture_1.jpeg)

# **Common Research Topics**

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

![](_page_36_Figure_7.jpeg)

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

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![](_page_37_Picture_0.jpeg)

# ... A Lot of Room for Research!

![](_page_37_Picture_2.jpeg)

- 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  $\rightarrow \rightarrow \rightarrow$

![](_page_38_Picture_0.jpeg)

![](_page_38_Picture_1.jpeg)

# ... 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, ...

![](_page_39_Picture_0.jpeg)

![](_page_39_Picture_1.jpeg)

# ... 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,...

![](_page_40_Picture_0.jpeg)

# **Overall Comparison of Major Renewable Energy Sources**

![](_page_40_Picture_2.jpeg)

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

![](_page_41_Picture_0.jpeg)

# Conclusion

![](_page_41_Picture_2.jpeg)

- Potential of wave energy as an up-andcoming 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?