Wave and Tidal Power: Projects and Prospects

by
George Hagerman
hagerman@vt.edu
Virginia Tech
Center for Energy and the Global Environment

Northeast CZM Partners Workshop
Virginia Beach, Virginia
07 October 2005
• **Wave Energy Resource**: A derived form of solar energy, in that unequal solar heating of the earth’s surface generates wind, and wind blowing over water generates waves.

• **Wave Energy Conversion Devices**: Three categories:
  – Terminator (OWC = oscillating water column, overtopping reservoir)
  – Attenuator (*Pelamis*)
  – Point Absorber (Heaving buoy, submerged float)

• **Tidal Energy Resource**: Astronomically-governed and thus highly predictable and relatively insensitive to weather conditions.

• **Tidal In-Stream Energy Conversion Devices**: Submerged turbine on monopile foundation has made most progress.

• **Electric Power Research Institute Projects**: Multi-year, collaborative efforts leading from feasibility definition study to design, construction, and operation of 500 kW demonstration projects:
  – Offshore Wave Energy Conversion (HI, WA, OR, SF, MA, ME)
  – Tidal In-Stream Energy Conversion (AK, WA, SF, MA, ME, NB, NS)
  – Hybrid Offshore Wind and Wave Energy Conversion (proposed)
The highest annual average solar energy flux at sea level is 300 watts per sq.m of horizontal area (i.e., solar cell surface area). At top of Earth’s atmosphere, the maximum solar energy flux available to orbiting satellites with sun-tracking solar panels is ~1,370 watts per sq.m.
Winds Move ~60% of Excess Solar Energy from Equator to Poles

Figure below shows nor’easter forming as cold dry air picks up heat and moisture from ocean.

Deep-ocean currents move the remaining ~40% (via thermohaline “conveyer belt”).
The highest average wind energy flux at the top of the Planetary Boundary Layer is 5,000 watts (5 kilowatts) per sq.m of vertical area (i.e. turbine rotor swept area).
Wind Over Water Generates Waves

Ocean swell can travel thousands of kilometers in deep water with negligible loss of energy. Thus wave energy produced anywhere in an ocean basin ultimately arrives at its continental shelf margins, virtually undiminished until it reaches ~200 m depths.
Calculation of Wave Energy Flux Density

Solar energy flux on a horizontal plane ≈ 1 kW per sq.m at noon on a clear day

Wave energy flux across a vertical plane (in kW per m of crest width) ≈ 0.5 × H_s^2 × \bar{T}_z

where H_s is significant wave height (in m) and \bar{T}_z is mean wave period (in sec)
Wave Energy Flux in Typical U.S. Mid-Atlantic Sea State

**Force 4**

**Wind Speed**: 11 to 16 knots (moderate breeze)

**Sea Criterion**: Small waves, becoming longer; fairly frequent white horses.

**Signif. Wave Height**: 1 to 1.5 m

**Peak Wave Period**: 4 to 5 sec

**Wave Energy Flux**: 2 to 6 kW/m
There are few exposed coastlines with annual average wave energy fluxes less than 5 kW/m.
OWC Terminator: Onshore LIMPET

500 kW demonstration project connected to utility grid on Islay, Scotland in November of 2000

Wavegen LIMPET: Land-Installed Marine Powered Energy Transformer
OWC Terminator: Energetech’s Nearshore Device

- Power Module
- Capture Chamber
- Parabolic Wall
- Mooring Lines
- Port Kembla 500 kW Demonstration Project
Parabolic Wall Yields ~4x More Energy
Overtopping Terminator: Wave Dragon
Prototype is 58 m wide (between tips of funneling side walls) and 33 m long, with a reservoir volume of 55 m$^3$ and a displacement of 237 metric tons. Total rated capacity is 17.5 kW.
Floating Attenuator: Pelamis

Power module contains two hydraulic cylinders that are stroked by relative pitch and yaw between adjacent segments.
750 kW Pelamis Demonstration Project

3.5 m dia x 150 m long

*Pelamis* 750 kW prototype installed in August of 2004 in 50 m water depth, 2 km offshore the European Marine Energy Centre, Orkney, UK
Point Absorber: Archimedes Wave Swing

2 MW prototype deployed May 2004 off northern Portugal

Upper, air-filled floater heaves up and down in response to waves passing overhead.

Permanent magnets fixed to floater (suspended from overhead) move relative to stator coil on anchor base.
Lunar Tidal Period is 24 Hours + 50 Minutes

Although it appears that the tidal bulge moves around the earth, the earth actually rotates beneath the lunar tidal bulge.

While the earth completes one daily rotation, the moon progresses slightly in its 27.3-day orbit around the earth. As a result, the earth must rotate an additional 50 minutes before any given location “catches up” with the lunar bulge.
The solar tidal bulge is only 46% as high as the lunar tidal bulge. While the lunar bulge migrates around the Earth once every 27 days; the solar bulge migrates around the Earth once every 365 days. As the lunar bulge moves into and out of phase with solar bulge, this gives rise to spring and neap tides.
A minimum site-specific measured record length of 369 days is needed in order to capture all significant tide forcing components, the most important eight of which are shown above. In the absence of strong onshore or offshore winds, tide predictions based on harmonic analysis of measured sea level records are generally accurate to within 3 cm in terms of water level and 5 minutes in terms of tidal stage.
Estimating Tidal In-Stream Energy Resources

Tidal Current Power Density

<table>
<thead>
<tr>
<th>$\rho$ (kg/m$^3$)</th>
<th>$V$ (knots)</th>
<th>$V$ (m/s)</th>
<th>$P/A_0$ (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.025</td>
<td>0.5</td>
<td>0.26</td>
<td>9</td>
</tr>
<tr>
<td>1.025</td>
<td>1.0</td>
<td>0.51</td>
<td>70</td>
</tr>
<tr>
<td>1.025</td>
<td>1.5</td>
<td>0.77</td>
<td>235</td>
</tr>
<tr>
<td>1.025</td>
<td>2.0</td>
<td>1.03</td>
<td>558</td>
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<tr>
<td>1.025</td>
<td>2.5</td>
<td>1.29</td>
<td>1,090</td>
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<tr>
<td>1.025</td>
<td>3.0</td>
<td>1.54</td>
<td>1,884</td>
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<tr>
<td>1.025</td>
<td>3.5</td>
<td>1.80</td>
<td>2,992</td>
</tr>
<tr>
<td>1.025</td>
<td>4.0</td>
<td>2.06</td>
<td>4,466</td>
</tr>
</tbody>
</table>

$P(t) = 0.5 \rho A_0 V^3(t)$
Revisiting the Passamaquoddy Tidal Project

THE TIDAL-STREAM ENERGY RESOURCE IN PASSAMAQUODDY-COBSCOOK BAYS: A FRESH LOOK AT AN OLD STORY

David A. Brooks
Department of Oceanography
Texas A&M University
UK-Based Marine Current Turbines

Marine Current Turbines
300 kW SeaFlow
(fully operational since May 2003)

Marine Current Turbines
1.2 MW SeaGen
(single unit to be installed 2006)
Tidal Stream Energy Devices in North America

Verdant Power horizontal-axis, (six-turbine, 200 kW test project to be installed in East River, NY)

UEK horizontal-axis, shrouded turbine (tests by Ontario Hydro)

GCK vertical-axis turbine (barge test on Merrimack River, MA)
## Renewable Energy Comparisons

<table>
<thead>
<tr>
<th>Development Status</th>
<th>Solar PV</th>
<th>Wind</th>
<th>Wave</th>
<th>Tidal Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Commercial</td>
<td>Early Commercial</td>
<td>Commercial</td>
<td>Pre-Commercial</td>
<td>Pre-Commercial</td>
</tr>
<tr>
<td>Source</td>
<td>Sun</td>
<td>Uneven solar heating</td>
<td>Wind blowing over water</td>
<td>Gravity of moon &amp; sun</td>
</tr>
<tr>
<td>Annual Average Power Density</td>
<td>200-300 watts/m² (southern &amp; western US)</td>
<td>400-600 watts/m² (US Great Plains)</td>
<td>20-25 kW/m (US West Coast)</td>
<td>3-5 kW/m² (Bay of Fundy)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5-15 kW/m (US East Coast)</td>
<td>1-2 kW/m² (other US sites)</td>
</tr>
<tr>
<td>Intermittency</td>
<td>Day-night; clouds, haze, and humidity</td>
<td>Atmospheric fronts and storms (local winds only)</td>
<td>Sea (local winds and swell (from distant storms)</td>
<td>Diurnal and semi-diurnal (advancing ~50 min./day)</td>
</tr>
<tr>
<td>Predictability</td>
<td>Minutes</td>
<td>Hours</td>
<td>Days</td>
<td>Centuries</td>
</tr>
</tbody>
</table>
EPRI North American Ocean Energy Projects

**Offshore Wave Energy Conversion (OWEC)**
- Phase 1: Project Definition Study
  - 2004
- Phase 1.5: Pre-Implementation Planning
  - 2005
- Phase 2: Design, Permitting, & Financing
  - 2006
- Phase 3: Construction
  - 2007
- Phase 4: Operation & Evaluation
  - 2008

**Tidal In-Stream Energy Conversion (TISEC)**
- Phase 1: Project Definition Study
  - 2005
- Phase 1.5: Pre-Implementation Planning
  - 2006
- Phase 2: Design, Permitting, & Financing
  - 2007
- Phase 3: Construction
  - 2009
- Phase 4: Operation & Evaluation
  - 2010

- Yellow: Completed
- Blue: In-progress
- Blank: Future
Offshore Wave Energy Resources in U.S. Exclusive Economic Zone

Total annual flux into all regions with avg. wave power density >10 kW/m is 2,230 TWh/year
Major North American Tidal In-Stream Energy Resources

- Cape Cod Canal
- Bay of Fundy
- Puget Sound
- San Francisco Bay
- Vancouver Island Strait of Georgia
- Alexander Archipelago
- Passamaquoddy Bay
- Cook Inlet
- Aleutian Islands
- Midway Island
- Johnson Island
- Hawaii
**Objective**

To demonstrate the feasibility of tidal in-stream power to provide efficient, reliable, environmentally friendly and cost-effective electrical energy and to create a push towards the development of a sustainable commercial market for this technology.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration</th>
<th>Key Activities</th>
<th>Cost</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I – Project Feasibility Definition Study</td>
<td>1 Year April 2005 to March 2006</td>
<td>Site survey &amp; characterization; Technology / device survey; Feasibility-level system design, performance analysis, life-cycle cost estimate and economic assessment; Environmental, regulatory and permitting issues</td>
<td>$350K</td>
<td>Maine Massachusetts New Brunswick Nova Scotia DOE EPRI San Francisco Alaska Washington</td>
</tr>
<tr>
<td>Phase II – System Design</td>
<td>12-18 Months</td>
<td>System Design, permitting and financing - 1 Site – Device</td>
<td>$500-1,000 K</td>
<td>Private owner or collaborative</td>
</tr>
<tr>
<td>Phase III - Construction</td>
<td>12 - 18 Months</td>
<td>1,500 MWh per year Plant (500 kW at 40% capacity factor)</td>
<td>$1,500 - 2,700 K</td>
<td>Private owner or collaborative</td>
</tr>
<tr>
<td>Phase IV - Operation</td>
<td>1-2 Years</td>
<td>Plant O&amp;M costs</td>
<td>$100-250K</td>
<td>Private owner or collaborative</td>
</tr>
<tr>
<td>Phase IV - Evaluation</td>
<td>1-2 Years</td>
<td>Additional cost due to RD&amp;D needs</td>
<td>$100-250K</td>
<td>50% DOE 50% EPRI</td>
</tr>
<tr>
<td>Total</td>
<td>5 - 7 Yrs</td>
<td></td>
<td>$3-5 M</td>
<td></td>
</tr>
</tbody>
</table>
Off Virginia, 3-mile limit of state jurisdiction roughly corresponds to 10 m water depth contour. In deeper waters “over the horizon,” mean annual wind power is 400-500 watts/m² of rotor swept area at 70 m hub height, and mean annual wave power is 4-5 kW/m of wave crest width.