DEVELOPMENTS IN WAVE ENERGY CONVERSION

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SUMMARY

- The resource
- The technologies
- The power take-off equipment
- The situation of wave energy conversion
- Wave energy conversion in the Mediterranean
THE RESOURCE
Typical values of wave energy flux per unit wave crest length (annual average)

Deep water: 4-70 kW/m

Near shore: lower values,
Depending on:
• bottom slope
• local depth (wave breaking)
• bottom roughness (friction)
• bottom configuration (diffraction, refraction)

Close to the surface (h<20m): density flux of energy (kW/m²) can be much higher than wind energy
The waves are generated by the wind.

In deep water ( > 100 - 200m ) they travel large distances (thousands of km) practically without dissipation.

The characteristics of the waves (height, period, etc.) depend on:

- **Sea surface area acted upon by the wind** *(large oceans versus Mediterranean)*
- **Duration of wind action**
World distribution of wave energy level
Annual-averaged values in kW/m (deep water, open sea)
Wave Energy Resource

• The total theoretical wave power resource in the oceans is very large: 1-10 TW (average world electrical power consumption: 2 TW).

• It is larger
  - off western coasts of the continents (Coriolis force)
  - in moderate to high latitudes

Average Annual Wave Power (kW/m)

From: Barstow, Mollison & Cruz.
Seasonal variations are much larger in the Northern Hemisphere than in the Southern Hemisphere (an important advantage).

Minimum Monthly Wave Power Relative to Annual

From: Barstow, Mollison & Cruz, 2008
Distribution of average power per unit crest length in the Mediterranean, 2001-2010

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Lon.</th>
<th>Lat.</th>
<th>Depth (m)</th>
<th>$J_{\text{mean}}$ (kW/m)</th>
<th>$E_{\text{annual}}$ (MWh/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cabo de Palos (Es)</td>
<td>$-0^\circ33'45''$</td>
<td>$37^\circ34'30''$</td>
<td>121</td>
<td>3.91</td>
<td>34.25</td>
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<td>2</td>
<td>Menorca (Es)</td>
<td>$4^\circ15'0''$</td>
<td>$40^\circ4'30''$</td>
<td>65</td>
<td>10.90</td>
<td>95.48</td>
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<tr>
<td>3</td>
<td>Cabo Creus (Es)</td>
<td>$3^\circ26'15''$</td>
<td>$42^\circ19'30''$</td>
<td>439</td>
<td>5.34</td>
<td>46.78</td>
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<tr>
<td>4</td>
<td>Hyères (Fr)</td>
<td>$6^\circ11'15''$</td>
<td>$42^\circ53'15''$</td>
<td>1476</td>
<td>6.47</td>
<td>56.68</td>
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<tr>
<td>5</td>
<td>Livorno (It)</td>
<td>$10^\circ11'15''$</td>
<td>$43^\circ30'45''$</td>
<td>83</td>
<td>3.24</td>
<td>26.02</td>
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<td>6</td>
<td>Ajaccio (Fr)</td>
<td>$8^\circ30'0''$</td>
<td>$41^\circ57'0''$</td>
<td>786</td>
<td>8.44</td>
<td>73.93</td>
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<td>7</td>
<td>Napoli (It)</td>
<td>$14^\circ7'30''$</td>
<td>$40^\circ30'45''$</td>
<td>782</td>
<td>3.51</td>
<td>30.70</td>
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<td>8</td>
<td>Crotone (It)</td>
<td>$17^\circ18'45''$</td>
<td>$39^\circ0'45''$</td>
<td>615</td>
<td>3.70</td>
<td>32.41</td>
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<td>Kefallonia (Gr)</td>
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<td>$38^\circ12'0''$</td>
<td>1512</td>
<td>4.91</td>
<td>43.01</td>
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<td>Ag. Gramvousa (Gr)</td>
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<td>374</td>
<td>7.10</td>
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<td>11</td>
<td>Skyros (Gr)</td>
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<td>269</td>
<td>5.16</td>
<td>45.20</td>
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<td>12</td>
<td>Gelydonia Burnu (Tr)</td>
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<td>1290</td>
<td>3.83</td>
<td>33.55</td>
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<td>14</td>
<td>Haifa (Il)</td>
<td>$34^\circ48'45''$</td>
<td>$32^\circ45'45''$</td>
<td>252</td>
<td>4.02</td>
<td>35.22</td>
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<td>15</td>
<td>Ras El-Kanayis (Eg)</td>
<td>$27^\circ52'30''$</td>
<td>$31^\circ19'30''$</td>
<td>420</td>
<td>5.30</td>
<td>46.43</td>
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<tr>
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<td>Ras Al Hilal (Ly)</td>
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<td>$35^\circ42'0''$</td>
<td>374</td>
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<td>57.73</td>
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<tr>
<td>17</td>
<td>Misrata (Ly)</td>
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<td>$32^\circ30'45''$</td>
<td>161</td>
<td>5.68</td>
<td>49.76</td>
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<tr>
<td>18</td>
<td>Ras Angela (Tn)</td>
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<td>$37^\circ27'0''$</td>
<td>250</td>
<td>9.25</td>
<td>81.03</td>
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<td>19</td>
<td>Cap Bougaouni (Dz)</td>
<td>$6^\circ26'15''$</td>
<td>$37^\circ12'0''$</td>
<td>2354</td>
<td>10.33</td>
<td>90.49</td>
</tr>
<tr>
<td>20</td>
<td>Orano (Dz)</td>
<td>$-0^\circ22'30''$</td>
<td>$36^\circ0'45''$</td>
<td>1428</td>
<td>5.15</td>
<td>45.11</td>
</tr>
</tbody>
</table>
Distribution of average power per unit crest length in the **Black Sea**, from 15-year hindcast data.
The wind velocity profile extends over several km.

A wind farm explores a tiny sublayer.

Most of the wave energy flux is concentrated near the surface.

A wave farm can absorb a large part of the wave energy flux.
THE TECHNOLOGIES
How far have we gone in 40 years? Some milestones:

- **1974**: Salter & the duck
- **1975-76**: Masuda & Kaimei
- **1975-82**: The early theoreticians
- **1991**: EU backs up wave energy
- **1996**: EURATLAS
- **1999-2000**: OWCs in Europe
- **2004-**: Since 2004

Years:
- **1985-91**: The early OWCs
- **1975-82**: The British Program
  - Goal: 2 GW plant

- **1991**: EU backs up wave energy
- **1996**: EURATLAS
Wave Energy Converter Types

Unlike the case of large wind turbines ...

... there is a wide range of wave energy devices, at different development stages, competing against each other.
Wave Energy Converter Types

Oscillating Water Column (with air turbine)
- Fixed structure
  - Isolated: Pico, LIMPET, Oceanlinx
  - In breakwater: Sakata, Mutriku
- Floating: Mighty Whale, BE3B, Spar Buoy

Oscillating body (hydraulic motor, hydraulic turbine, linear electric generator)
- Floating: Aquabuoy, IPS Buoy, Wavebob, PowerBuoy, FO3
- Pitching: Pelamis, PS Frog, Searev, SeaRay
- Heaving: AWS
- Bottom-hinged: Oyster, Waveroller

Overtopping (low head water turbine)
- Fixed structure
  - Shoreline (with concentration): TAPCHAN
  - In breakwater (without concentration): SSG
- Floating structure (with concentration): Wave Dragon
Wave Energy Converter Types

Different ways of classifying WECs:

- Shoreline
- Nearshore
- Offshore

According to working principle

- Point absorber
- Multibody
- Large absorber
- Terminator
- Attenuator
Wave Energy Converter Types

OWC (Oscillating Water Column)

Cross-section of bottom-standing OWC plant.
Earlier OWC prototypes: the structure is fixed to the bottom

- Japan
- India
- Portugal
- UK
- China
- Australia
- Spain
Floating OWCs are more appropriate for large-scale exploitation of wave energy.
OWC: floating

Spar-buoy OWC

At Nazaré, Portugal, 2012.

1:16 scale model at NAREC, UK, October 2012.
Oscillating Bodies

SeaRay, USA

PowerBuoy, USA

CETO, Australia

Bolt, Norway
Multibody

WaveStar, Danmark

1/10th scale

Hyperbaric converter, Brazil

1/2 scale
Floating, Multibody,

Pelamis, UK

3-unit farm, Portugal, 2008.

New Mark 2 version
Submerged, Bottom-hinged, Nearshore

Oyster, UK

At EMEC, Scotland, 2010
WaveRoller, Finland

Submerged, Bottom-hinged, Nearshore

The concept

3 x 100 kW, being installed at Peniche, Portugal, 2012
Demonstration – Wave (SWEDEN)

Sotenäs Demonstration project

- **Seabased Industry**, spin-off from the wave energy research at Uppsala University.
- Demonstration wave park
  - 10 MW, ~400 WECs
  - € 29M
  - Under construction since early 2012.
THE POWER TAKE-OFF EQUIPMENT
Special air turbines for oscillating-water-column plants

WELLS

IMPULSE
Linear electric generator

High-head hydraulic turbines

Uppsala University, Sweden

Oyster

Brazil
High-pressure-oil PTO

Pelamis

Wave Star

Wave Roller

WaveBob

PowerBuoy
THE SITUATION OF WAVE ENERGY CONVERSION
A few basic concepts:
• Oscillating water column (OWC)
• “point absorber”
• large oscillating-body (multi-body)
• run-up device, ...

A large number of designs (>50) of which a few (≈15?) reached (or are close to) the prototype stage.

There are several effective ways of absorbing energy from the waves.

No technology appears to be dominant (unlike wind).
Like in life, will there be a Darwinian preservation of favoured wave energy converter designs in the struggle for the market? How long will it take? Which one(s) will be the **winner(s)**?
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**Oscillating Water Column** (with air turbine)

- Fixed structure
- In breakwater: Mutriku

**Oscillating body** (hydraulic motor, hydraulic turbine, linear electric generator)

- Floating: Mighty Whale, BBDB
- Isolated: Pico, LIMPET, Oceanlinx
- Fixed structure: TAPCHAN
- In breakwater (without concentration): SSG
- Floating structure (with concentration): Wave Dragon

**Overtopping** (low head water turbine)

- Floating: Pelamis, PS Frog, Searev
- Fixed structure (with concentration): TAPCHAN
- Floating structure (with concentration): Wave Dragon

**Submerged**

- Heaving: AWS
- Pitching: Pelamis, PS Frog, Searev
- Bottom-hinged: Oyster, Waveroller
Possibly the “most difficult” of the renewables.

From the development and economic point of view, the situation is similar to wind in the 1980s?

Except for a small number of cases, there is little or no experience of maintenance, reliability and survival (under extreme conditions) in real open-sea, for more than a few months.

The most advanced technologies are at the pre-commercial stage.
For most technologies, the **capacity factor**: annual-averaged power divided by rated power, is similar to wind (\(~0.3–0.35\) (possibly larger in the **southern hemisphere** due to smaller seasonal variations).

At the present stage of technology development, the unit cost of electricity from waves ranges **between wind and large photovoltaics**.

In order to be competitive with onshore wind, a cost reduction factor of about 3 will be required for the best designs (2 or less if compared with offshore wind).

**As for wind, the extensive exploitation of wave energy will require large **arrays or farms****.
WAVE ENERGY CONVERSION IN THE MEDITERRANEAN
The level of wave energy resource in most of Mediterranean is substantially lower than in the large oceans.

Yet, attempts are being made to use that energy!
• Most of the Research & Development is taking place in Italy.

• Combine caisson breakwaters for harbour protection with energy production from waves.

• Technology: oscillating water column with air turbines.

• This is being done in coastal areas of low wave energy content.
New harbour breakwaters to include wave energy absorption:

- Civitavecchia (near Rome)
- Pantelleria island (between Sicily and Tunisia)
The technology: U-shaped oscillating-water-column in a caisson breakwater
Enlargement of Civitavecchia harbour
Enlargement of Civitavecchia harbour

Cross-section of the REWEC3 wave energy converter in the Civitavecchia harbour

REWEC3 caisson at the preliminary stage, before placing in situ (2012-2013).

Port of Pantelleria
Thank you for your attention