WP7: Lifetime Economics of Marine Energy Converters

Supergen WP7
A comparative study of wave energy technologies

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Plan

- Overview of Economic Studies
- Economic Considerations
- Scheme requirements (functions)
- Cost to generate electricity,
  - Modelling approaches – COE present and future
  - Capital & Operating cost: Factors affecting & data sources
  - Electricity production
- Technology comparison(s)
- Work in progress
WP7 Remit

• Suggest design features that are likely to improve the economic viability of offshore wave/tidal projects at large scales of installation.
  – Through consideration of full-life costs
• Provide inputs for Macro-Economic study (WP12)
  – Probable range of cost to generate electricity by offshore renewables at different scales of installation
  – Estimation of investment in different industry sectors
Future Cost

How can we obtain an estimate of future COE?

• Use learning curves from ‘comparable’ industries..
  Progress Ratios for wind turbines found to vary between 77-96% (Junginger, 2004 and Neij et al. 2003) but.. “choice of time frame, geographical area, GDP-deflator, etc., can cause significant differences in the resulting progress ratios.”
  Junginger (Energy Policy 33, 2004)

• Investigate feasibility of cost reduction by economies of scale..
  Which WEC devices / scheme components will benefit from mass production?
    e.g. wind turbines (Junginger et al. 2005) and Ford engines (Roy 2005)
  Are wave climates sufficiently similar for mass production to be beneficial?

• Cost of Electricity from large scale multi-MW installations
  - power output dictated by sea-state (location) and device characteristics
  - cost strongly influenced by device design and scheme configuration choices
Economic Model

- $P_{RAT\text{E}D}$: Rated Capacity
- Conversion Technology
- Wave Climate / Tidal Range
- Site characteristics
- $N_{ME\text{C}}$: Number of Devices
- $P_{AAP}$: Annual Average Power
- Financial Parameters
- $E_{\text{cap}}$: Capital Expense
- $E_{\text{Ann}}$: Annual Expense
- CGE: Cost to Generate Electricity
Levelized Cost

Estimate CGE (p/kWh) as “Present value of cost per kWh of electricity produced which allows the scheme to break even over the project lifespan.”

Model cash flow over $N$ yrs based on uncertain inputs inc:

- $E_{cap}$, $E_{Ann}$, overhaul, decommissioning, and revenue from electrical output only.
Capital Expenses, $Ex_{cap}$

- $Ex_{SI(Civil)}$: Capital Expense due to water depth, line and anchor load
- $Ex_{SI(Elec)}$: Capital Expense due to array configuration and cable cost
- $Ex_{MEC}$: Capital Expense due to material mass and principal components
- $Ex_{O/H}$: Capital Expense due to distance to grid connector and power output

Diagram:

- Array Configuration
- Scheme Validity
  - $N_{MEC}$: Number of Devices
- Conversion Technology
  - $P_{RATED}$: Rated Capacity
- $Ex_{SI(Civil)}$: Mooring Cost
  - $Ex_{SI(Elec)}$: Inter-Array Cables
  - $Ex_{Device}$: MEC Device Cost
  - $Ex_{O/H}$: Site-grid Transmission
- $Ex_{cap}$: Capital Expense
Ex_{cap} Data

• Devices
  – Cost estimation studies for diverse range of technologies:
  – CT Report (e.g. Frog) – Aug 05, Previsic (2004), Thorpe (1999)
• Civil Infrastructure
  – Mooring Lines: WP8, Harris et al. (WREC 04), O&G Reports
• Electrical Infrastructure
  – Offshore Wind (e.g. AEI Cables), CT
  – Cable – Device connections (limited knowledge at present)
• Site Overheads
  – Wavehub Reports (2001-05), Previsic (2004-Pelamis)
  – Network connection costs
Annual Expenses, $Ex_{Ann}$

$T_{req}$: dependent on –
  i) number of scheme components, 
  ii) maintenance requirements
  iii) probability of failure and repair time
  iv) distance from port to site

$T_{acc}$: dependent on –
  i) vessel characteristics,
  ii) wave climate at site
  iii) Current range at site
Wave Conditions for O&M

- Annual probability of wave height occurrence
  \[ P(H_s < 2 \text{ m}) \sim 0.78 \]

- Monthly variation of accessible wave conditions
  \[ 0.1 < P(H_s < 2 \text{ m}) < 0.9 \]

- Monthly variation of accessible wave conditions occurring for useful interval.
  \[ 0.1 < P(H_s < 2 \text{ m}, t_{ac} > 6 \text{ hr}) < 0.8 \]
Offshore Operations

• Vessel rates – major component of O&M cost.
  • Rental: Unreliable day rates due to market - £2k - £40k variations
  • Purchase: Uneconomic due to low utilization rate (?)
  • Viability (and risk) related to site accessibility

  – Vessel Types:
    • Special Purpose WEC vessels
      – Predicted costs? performance advantages?
    • Standard Oil & Gas industry vessels: AHTS, OSV, Crew, Tug
      – Relatively inefficient for MEC applications

• Crew Rates:
  – Inclusive to vessel rates.
1. Simplistic estimate of device output by load factor

\[ E_{out} = P_{RATED} \times e_{tot} \times t_{yr} \]

2. By site wave climate data and WEC performance data:
# WEC Categories

## Oscillating Absorbers

<table>
<thead>
<tr>
<th>Overtopping</th>
<th>Pneumatic</th>
<th>Independent</th>
<th>Clustered</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWPV</td>
<td>Sea Clam</td>
<td>Sloped IPS Buoy</td>
<td>IPS OWEC Aquabuoy</td>
</tr>
<tr>
<td>WaveDragon</td>
<td>Mighty Whale</td>
<td>Frog (Mk5 and 6)</td>
<td>OPT PowerBuoy</td>
</tr>
<tr>
<td>WavePlane</td>
<td>OWeL</td>
<td>Russell Rectifier</td>
<td>WaveBob</td>
</tr>
<tr>
<td>Wavemaster</td>
<td>Energetech</td>
<td>(Solo) Duck</td>
<td>Budal &amp; Falnes Buoy</td>
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<tr>
<td></td>
<td>Embley Sperboy</td>
<td>Pelamis</td>
<td>Danish Point Absorber</td>
</tr>
<tr>
<td></td>
<td>Orecon</td>
<td>McCabe Wave Pump</td>
<td>SeaDog</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OTD</th>
<th>Pn</th>
<th>IOA</th>
<th>COA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>0.33</td>
<td>0.22</td>
<td>0.39</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>0.81</strong></td>
<td><strong>0.22</strong></td>
<td><strong>0.39</strong></td>
<td><strong>0.05</strong></td>
</tr>
</tbody>
</table>

$P_{\text{RATE}}(\text{MW})$ and $e_{\text{tot}}$ indicative of developer claims.

$P_{\text{OUT}}(\text{MW})$
### 100MW Scheme: $Ex_{Cap}$

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<th>COA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{MEC}$ (MW)</td>
<td>0.81</td>
<td>0.22</td>
<td>0.39</td>
<td>0.05</td>
</tr>
<tr>
<td>$N_{MEC}$</td>
<td>38</td>
<td>139</td>
<td>89</td>
<td>613</td>
</tr>
<tr>
<td>$L_{moor}$ (km)</td>
<td>6</td>
<td>21</td>
<td>13</td>
<td>92</td>
</tr>
<tr>
<td>$L_{elec}$ (km)</td>
<td>34</td>
<td>22</td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>$A$ (km$^2$)</td>
<td>33</td>
<td>5.2</td>
<td>1.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Note: Device cost ($Ex_{MEC}$) excluded

![Graph](chart.png)
## 100MW Scheme: $E_{x}^{Ann}$

<table>
<thead>
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<tbody>
<tr>
<td>$N_{MEC}$</td>
<td>38</td>
<td>139</td>
<td>89</td>
<td>613</td>
</tr>
<tr>
<td>$N_{O&amp;M/MEC}$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$MTTR$ (hrs)</td>
<td>1.5</td>
<td>2</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$T_{OMReq}$ (days)</td>
<td>13</td>
<td>56</td>
<td>30</td>
<td>307</td>
</tr>
</tbody>
</table>

![ExVessel (£Myr)](chart.png)

- **Rented**
- **Commissioned**

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## Scheme comparison

| Type | $P_{\text{RATE}}$ (MW) | $e_{\text{cap}}$ | $e_{\text{PTO}}$ | $e_{\text{tot}}$ | $N_{\text{MEC}}$ | $k_p$ (£k/kW) | $k_{\text{MEC}}$ (£k) | $k_{\text{MEC}}/k_{\text{COA}}$ |
|------|-----------------|------------|----------|-----------|---------------|------------|------------|----------------|----------------|
| OAC  | 0.125           | 0.2        | 0.7      | 0.140     | 57.14         | 362        | 45         | 1.0            |
| OAI  | 1               | 0.45       | 0.75     | 0.338     | 2.96          | 874        | 874        | 19.3           |
| OTD  | 2.5             | 0.4        | 0.81     | 0.324     | 1.23          | 839        | 2097       | 46.3           |
| Pn   | 1               | 0.4        | 0.54     | 0.216     | 4.63          | 559        | 559        | 12.3           |

Capital cost per MEC device ($k_{\text{MEC}}$) for $E_{\text{Ann}}=6\%E_{\text{Cap}}$ and a target CGE=5p/kWh

Ratio between capital expense budget per IOA, OTD and Pn devices ($k_{\text{MEC}}$) and the capital expense budget per COA device ($k_{\text{COA}}$) for range of O&M and target CGE.
Electrical Output (2)

1. Simplistic estimate of device output by load factor

\[ E_{out} = P_{RATED} \times e_{load} \times t_{yr} \]

2. By site wave climate data and WEC performance data:

\[ E_{out} = \int_{T_{\text{min}}}^{T_{\text{ex}}} \int_{H_{\text{min}}}^{H_{\text{ex}}} t_{\text{sea-state}}(H_s, T_z) \times P_{MEC}(H_s, T_z) \cdot dH_s \cdot dT_z \]

- Wave climate recorded as series of irregular sea states -
  Each irregular sea-state characterised by a wave height (e.g. \( H_s \)) and period (e.g. \( T_z \))
- WEC performance in each irregular sea-state affected by -
  • Rated capacity of device – upper limit to output in any sea-state
  • Optimisation of mean power output in each irregular sea-state
  • Range of sea-states within which optimal output can be attained
### Sea State Occurrence:

\( T(H_s, T_z) \) South Uist: Shaw, 1982

| 0.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 0.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 1.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 1.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 2.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 2.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 4.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 4.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 5.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 5.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 6.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 6.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 7.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 7.75 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 8.25 | 3 | 2 | 5 | 3 | 8 | 10 | 12 | 10 | 10 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

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### Irregular wave spectra:

- e.g. P-M, Jonswap, Bretschneider Measured

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- **Pierson Moskowitz**

- **JONSWAP \( (\gamma=3.3) \)**

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- Irregular wave spectra: measured

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- **Pierson Moskowitz**

- **JONSWAP \( (\gamma=3.3) \)**

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- Power spectrum of wave height

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- Time series of wave height

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Annual Output

\[ E_{out} = \int_{T_{min}}^{T_{ex}} \int_{H_{min}}^{H_{ex}} \left( H_s, T_z \right) \times P_{MEC} \left( H_s, T_z \right) \cdot dH_s \cdot dT_z \]

\[ T(H_s, T_z) \text{ South Uist: Shaw, 1982} \]

\[ P_{MEC} \text{ Pelamis: oceanpd.com (optimal)} \]
Annual Output (Pelamis)

\[ E_{out} = \int_{T_{\text{min}}}^{T_{\text{ex}}} \int_{H_{\text{min}}}^{H_{\text{ex}}} t_{\text{sea-state}}(H_s, T_z) \times P_{\text{MEC}}(H_s, T_z) \cdot dH_s \cdot dT_z \]

\( t_{\text{sea-state}} \) Aggregate duration (hrs) of sea-states characterised by \( H_s \) and \( T_z \)

\( P_{\text{MEC}} \) Mean power output (kW) of device in sea-state characterised by \( H_s \) and \( T_z \)
Transient Output

Variation of power output in 3 hour increments May01-May05:
- UKMO (modelled) / BODC (measured) sea-state ($H_s$, $T_z$) data
- Device output dictated by rated capacity, sea-state optimisation, sea-state ‘tuning’

Development of transient output model
- Site similarities in energy content and temporal variation scales
- Continuity of supply, electricity demand correlation

(Wave Data Supplied by UKMO, Based on Pelamis power capture matrix)
Seasonal Output

Output during each quarter for the Pelamis power capture matrix in a range of wave climates within UK waters.

% of annual output and revenue generated during winter months (Q1 and Q4) at 8 sites
(Wave data supplied by UKMO, electricity value from Elexon)
Idealised Device

Oscillating capture element,
natural frequency=$1/T_N$

Broad Bandwidth Device, $T_N=8.25$ s

Narrow Bandwidth Device, $T_N=8.25\pm1$ s shown

Transient Output

Winter=261±30and Summer=50.3±126

Winter=181±221and Summer=31.4±100 (untuned)
Uncertainties (WP7)

• Uncertainty of output from different technologies
  – characteristics of operational irregular sea-states
  – performance of different technologies within irregular sea-states
  – revenue increase attained by use of ‘tuning’ systems.

• Reliability of MEC technologies
• Influence of maintenance strategy on availability
• Future cost reductions of both capital cost and market value
• Limitations imposed by direct electrical transmission
Summary

WP7 aims to provide insight into the device characteristics (capital cost and maintenance requirements) that would make different technologies competitive at different scales of installation.

– Estimate the transient revenue on the basis of performance surface
– Estimate number of devices required to produce specified output
– Obtain probable range of non-device capital expenses
– Determine the range of device costs that would produce economical CGE
– Compare target costs to prototype cost estimates (e.g. MEC I)
Notes
Learning Curves

“The most difficult problem associated with devising learning curves is obtaining suitable and accurate data… the learning curve function should be calculated only when considerable volume of data is available.”


“…care needs to be taken to distinguish between:

i) increases in labour productivity due to learning (shift along a learning curve)

or

ii) improvements due to fundamental changes in the production process (resulting in shift to new learning curve).”


“…a derived learning rate must not be used to extrapolate beyond two orders of magnitude from the supporting data”

IEA (2000)

“We are interested in the reliable estimation and forecasting of renewable energy technology costs, ... The results presented here caution against the estimation of experience on the basis of a single right-hand side variable as this may mask underlying statistical insignificance.”

Papineau (Energy Policy, 2005)
Volume Production


Sea-state Accessibility

Winter Statistics

Summer Statistics

Probability of accessible wave height occurring at random sample time (Previsic 2004 Pelamis)

Probability of accessible conditions persisting for interval $\tau_{ac}$ (BMT 2001)

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Operation Viability

Winter Statistics

Summer Statistics

Probability of accessible wave height occurring at random sample time (Previsic 2004 Pelamis)

Probability of completing task of duration $\tau_{OM}$ (Herman, 2002)

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