Combining Offshore Wind and Wave Energy Farms to Facilitate Grid Integration of Variable Renewables

Why Offshore?          Resource          Technology          Offshore Wind & Wave

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Atmosphere/Energy Program

Photo credit: Hywind / Trude Refsahl / Statoil
Photo credit: Pelamis Wave Power, LTD
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Why Offshore?
- Resource
- Technology

Offshore Wind & Wave

Offshore Platform
- Wind or Wave Energy Converters
- Generators
- Transformers
- Collector Cable

Converter Station
- Submarine Cables
Combining Wind and Wave Energy

Reduce Grid Integration Requirements for Variable Renewables

Reduce Offshore Transmission Infrastructure Capacity

Increase Renewable Energy Yield per km² of Ocean Space

Design and Operating Synergies to Reduce Costs
- 53% of the US population lives in coastal counties
- An estimated 40% of the world population lives within 100 kilometers of the coast
Why Go Offshore for Renewable Energy?

Why Offshore?

Resource          Technology          Offshore Wind & Wave
Pacific Offshore Wind Energy Resource

Offshore Wind GIS Data, NREL 2010
Pacific Wave Energy Resource

Mapping and Assessment of the United States Ocean Wave Energy Resource, EPRI 2011

Why Offshore?

Resource

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Offshore Wind & Wave
California Combined Offshore Wind and Wave Energy Resource

Offshore Wind GIS Data, NREL 2010
Mapping and Assessment of the United States Ocean Wave Energy Resource, EPRI 2011

NDBC Buoys

NOAA NDBC

US Combined Offshore Wind & Wave Energy Resource

- **Class 5**: Wind > 9.75 m/s & Wave > 45 kW/m
- **Class 4**: Wind > 9.50 m/s & Wave > 40 kW/m
- **Class 3**: Wind > 9.25 m/s & Wave > 35 kW/m
- **Class 2**: Wind > 9.00 m/s & Wave > 30 kW/m
- **Class 1**: Wind > 8.75 m/s & Wave > 25 kW/m

Why Offshore?  Resource  Technology  Offshore Wind & Wave
Wind Driven Wave Generation

Co-located Wind and Wave Resources

Wind Power

Northern Hemisphere Winter

Northern Hemisphere Summer

Why Offshore?

Resource

Technology

Offshore Wind & Wave
Offshore Wind Technology

Technology
6.15 MW turbines installed
126 m rotor diameter
Larger designs coming

Market
53 wind farms
3,810 MW installed
866 MW in 2011
5,600 MW under development

European Wind Energy Association, 2011
The Challenge of Wave Energy Device Design

<table>
<thead>
<tr>
<th>Super-structure/Vessel</th>
<th>Power Transmission</th>
<th>Power Conversion(s)</th>
<th>Power Extraction/Absorption</th>
<th>Electrical Cables</th>
<th>Generator: Hydraulic Low Head Air</th>
<th>Power Absorbing Device/Medium &amp; Reaction Point</th>
</tr>
</thead>
<tbody>
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</table>

Stochastic, low frequency mechanical energy

Wave Energy

Constant, high frequency (50/60 Hz) electrical energy

Electrical/Hydraulic Energy

Dude, where’s my wave energy?

Why Offshore? Resource Technology Offshore Wind & Wave
Combining Wind and Wave Energy

StatoilHydro’s Hywind Project

Pelamis Wave Energy Converter

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- Reduce the variability of the aggregate power output
- Reduce the forecast error of the aggregate power output

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Design and Operating Synergies to Reduce Costs
Data Source: NDBC Buoys

**Methodology**

Why Offshore?

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Offshore Wind & Wave

Methodology

Installed Capacity (MW)
1. 100% Wind
2. 75% Wind – 25% Wave
3. 50% Wind – 50% Wave
4. 25% Wind – 75% Wave
5. 100% Wave
Wind power output correlation versus distance between UK sites

2,080 pairs of wind sites - based on UK long term average CF of 30%

Fig. 5. UK wind speed correlation by distance between recording sites.
California Wind and Wave Power - 12 buoy locations

Distance between sites [km]

Hourly Power Output Correlation - $r$

-0.2
0
0.2
0.4
0.6
0.8
1

0 100 200 300 400 500 600 700 800 900 1000
California Wind and Wave Power - 12 buoy locations

Hourly Power Output Correlation - $r$

Distance between sites [km]

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California Wind and Wave Power - 12 buoy locations

Distance between sites [km]

Hourly Power Output Correlation - r
Geographic and Resource Correlations

California Wind and Wave Power - 12 buoy locations

Hourly Power Output Correlation - $r$

Distance between sites [km]

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Geographic and Resource Correlations

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Offshore Wind & Wave

California Wind and Wave Power - 12 buoy locations

Hourly Power Output Correlation - r

Distance between sites [km]
Power Output Frequency Profiles

100% wind farm

Probability of occurrence

% of rated power output

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Power Output Frequency Profiles

100% wave farm

Why Offshore?  Resource  Technology  Offshore Wind & Wave
Combined farms with wind and wave

Power Output Frequency Profiles

Why Offshore?
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Offshore Wind & Wave
Reduce Hours of Zero Power Output

Hours of no power output

100% Wind Power
1334 hours

75%-25% Wind
296 hours

50%-50% Wind
115 hours

25%-75% Wind
70 hours

100% Wave Power
242 hours

Simplified California Electric Power System

Why Offshore?

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Offshore Wind & Wave

Offshore Wind

Wave

Combined Cycle Gas Turbine

California System Load
**Capacity Value Model**

**Generation = Load**

- **Generation**
  - Capacity Outage Probability Table

- **Load**
  - Peak Load Probability Table

**Loss of Load Index**

- **Add Renewables (MW)**
- **Increase in Load Served (MW)**

**Capacity Value = Increase in Load Served**

**Capacity Factor = Average Power Output**

### Capacity Value Model

**System Integration Value = Capacity Value/Capacity Factor**

**System Integration Value = Power that meets Peak Load/Average Power Supplied**

<table>
<thead>
<tr>
<th>Generation Mix</th>
<th>100% wind</th>
<th>75%-25%</th>
<th>50%-50%</th>
<th>25%-75%</th>
<th>100% wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Integration Value</td>
<td>66%</td>
<td>74%</td>
<td>83%</td>
<td>88%</td>
<td>75%</td>
</tr>
</tbody>
</table>
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- Reduce the hours of zero power output and increase the capacity value of the farm
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Reduce Offshore Transmission Infrastructure Capacity
- Compared to an equivalently sized offshore wind farm, less transmission capacity is required for a combined farm

Increase Renewable Energy Yield per km² of Ocean Space

Design and Operating Synergies to Reduce Costs
Transmission Design Case Study

Example HVDC Layout

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Transmission Optimization Problem

Combined farms with wind and wave

Why Offshore? Resource Technology Offshore Wind & Wave
50% wind : 50% wave farm
Transmission Optimization Problem

50% wind : 50% wave farm

[Graph showing percent of rated power output versus percent of the hours in a year, with a shaded area indicating the optimization target.]
Transmission Optimization Problem

50% wind : 50% wave farm

- Curtailed Energy
- Lost Revenue
- Reduce Transmission Capacity
- Capital Cost Savings

Why Offshore?

Resource

Technology

Offshore Wind & Wave
# Results

<table>
<thead>
<tr>
<th>Transmission Capacity in MW</th>
<th>Buoy 46030</th>
<th>Buoy 46028</th>
<th>Buoy 46013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 km  40 km  50 km  60 km</td>
<td>30 km  40 km  50 km  60 km</td>
<td>30 km  40 km  50 km  60 km</td>
</tr>
<tr>
<td>100% Wind</td>
<td>956  956  956  956</td>
<td>956  956  956  956</td>
<td>956  956  956  956</td>
</tr>
<tr>
<td>75% Wind : 25% Wave</td>
<td>874  874  874  874</td>
<td>874  874  874  874</td>
<td>874  874  874  874</td>
</tr>
<tr>
<td>50% Wind : 50% Wave</td>
<td>874  874  874  874</td>
<td>874  874  874  874</td>
<td>874  874  874  874</td>
</tr>
<tr>
<td>25% Wind : 75% Wave</td>
<td>874  874  874  874</td>
<td>874  874  874  874</td>
<td>874  874  874  874</td>
</tr>
<tr>
<td>100% Wave</td>
<td>956  956  956  956</td>
<td>874  874  874  874</td>
<td>956  956  956  874</td>
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8% Reduction in Transmission Capacity

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Increase Renewable Energy Yield per km² of Ocean Space
- Harness two co-located renewable energy resources
- Reduce array wake losses

Design and Operating Synergies to Reduce Costs
Combining Wind and Wave Energy

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Increase Renewable Energy Yield per km$^2$ of Ocean Space
- Harness two co-located renewable energy resources
- Reduce array wake losses

Design and Operating Synergies to Reduce Costs
- Share common infrastructure and equipment on and offshore
- Share permitting and project development costs
- Share operating and maintenance costs
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