Mapping O&M Strategy for US offshore wind farms

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2nd US Offshore Wind Conference & Expo
Overview

Reference O&M Concepts for Near and Far Offshore Wind Farms
- Understand impacts of metocean conditions on O&M costs
- O&M study of 5 offshore wind plants in the North Sea
- Tool: ECN O&M Access Tool
- December 2016

A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015-2030
- Quantify the impact of spatial characteristics of the U.S. offshore wind resource area on LCOE
- O&M specific tool: ECN O&M Tool
- September 2016

Mapping O&M Strategy for U.S. Offshore Wind Farms
- Collaboration between ECN and NREL
- O&M study of 6 offshore wind plants in the U.S.
- Tool: ECN O&M Calculator
- Anticipated joint publication 2017
NREL’s Spatial-Economic Analysis

The analysis considers:

- 4 access strategies
  - Close to shore
  - Advanced close to shore
  - Medium distance
  - Far shore

- 3 types of large maintenance strategies
  - In situ
  - Tow to port
  - Tow to assembly area

Key variables:
1. Distance from O&M port
2. Metocean conditions
## Distance from O&M Port

### Metocean Conditions

<table>
<thead>
<tr>
<th>Distance to O&amp;M Port (km)</th>
<th>&quot;Mild&quot; Site</th>
<th>&quot;Moderate&quot; Site</th>
<th>&quot;Severe&quot; Site</th>
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<tbody>
<tr>
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<td>Mean Hs = 0.88 m</td>
<td>Mean Hs = 1.39 m</td>
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\(^a\) Mean wind speed at 10 m above mean sea level
\(^b\) Close to shore
\(^c\) Medium distance
\(^d\) Far shore

**Photo courtesy of Atlantic Wind Transfers**

Image copyright © Mercator Media 2017

Source: http://www.esvagt.com
Representative Metocean Conditions

- **Mild**
  - $H_s \sim 0.88$ m

- **Moderate**
  - $H_s \sim 1.39$ m

- **Severe**
  - $H_s \sim 2.5$ m
Total O&M Costs for Moderate Site with Turbine on Fixed-Bottom Substructure

Identifies least cost choice among the 4 access strategies.
Distance to Harbour

- Ashtabula: 30 km
- New York City: 70 km
- Kitty Hawk: 143 km
- Corpus Christi: 102 km
- Honololui: 22 km
- Hueneme: 127 km
Water Depth Sub-Structure

- 575 m Floating
- 30 m Fixed-bottom Mono-bucket (ice breaker)
- 20 – 40 m Fixed-bottom
- 30 m Fixed-bottom
- 700 m Floating
- 30 m Fixed-bottom
MetOcean Conditions

- Avg. Wind Speed: 10.49 m/s
  Avg. Wave Height: 2.01 m

- Avg. Wind Speed: 8.30 m/s
  Avg. Wave Height: 1.34 m

- Avg. Wind Speed: 8.84 m/s
  Avg. Wave Height: 1.08 m

- Avg. Wind Speed: 8.32 m/s
  Avg. Wave Height: 1.35 m

- Avg. Wind Speed: 7.05 m/s
  Avg. Wave Height: 0.52 m
Location Challenges

- Deep water: >500 m deep
- Hurricanes: June 1st – Nov 30th
- Ice: 11 weeks per year

Map of the United States highlighting:
- Great Lakes
- Pacific
- Atlantic & Gulf of Mexico

- Hurricanes: June 1st – Nov 30th
Gemini (North Sea)

600 MW (150 x 4MW)
Eemshaven, 85 km
~ 30 m deep, Fixed Bottom
W_s & W_h: 9.49 m/s & 1.55 m
Far-offshore wind farm site (North Sea standards)
Atlantic & Gulf of Mexico; Gemini (North Sea)

- 600 MW (150 x 4MW)
- 85 km
- ~ 30 m deep, Fixed Bottom
- $W_s$ & $W_h$: 9.49 m/s & 1.55 m

New York Kitty Hawk
Gulf of Mexico

- 600 MW (100 x 6MW)
- Between 70 km & 143 km
- ~ 30 m deep, Fixed Bottom
- $W_s$ & $W_h$: ~ 8.68 m/s, ~ 1.25 m
O&M Strategies: Selection of the right mix of logistic solution.

**Primary Vessels**
- **CTV** 12 m/s, 1.5 m
- **CTV+** 15 m/s, 2.0 m
- **SES** 17 m/s, 2.5 m
- **SOV** 20 m/s, 3.0 m

**Secondary Vessels**
- **Daughter craft** 10 m/s, 1.0 m
- **Helicopter** 20 m/s, 4.0 m
- **Jack-up barge** 10 m/s, 2.0 m

**Vessels for replacement**
O&M Strategy: Selection of the logistic solution for Gemini

SOV
20 m/s, 3.0 m

Primary access Vessel

Secondary access Vessel

Helicopter
20 m/s, 4.0 m

Daughter craft
10 m/s, 1.0 m

Vessel for Replacement

Jack-up barge
10 m/s, 2.0 m
Validated with ECN O&M Calculator:

**SOV & Helicopter combined strategy**

Availability (Time & Yield): 95-96%
Repair Costs (M$/year): 40
Atlantic & Gulf of Mexico; Gemini (North Sea)

Repair Costs (M$/yr)

~20% difference

New York
Kitty Hawk
Gulf of Mexico
Difference in O&M Costs: US & Europe

- New York: 21%
- Kitty Hawk: 20%
- Gulf of Mexico: 18%

Atlantic & Gulf of Mexico; Gemini (North Sea)
How to reduce the difference in repair costs?

Optimisation and Selection of the “most suitable O&M Strategy” with ECN O&M Calculator

- Criterion of min 95% availability (time and yield)
- Highest availability with a cost-effective solution
Outcomes

- SOV, SOV & Heli, SES give the best solutions in terms of availability (95%)
- SES is the most suitable O&M strategy
Outcomes

- SOV or SOV & Heli provide the highest availability
- SOV is the most cost-efficient strategy

<table>
<thead>
<tr>
<th>O&amp;M Strategy implemented</th>
<th>Costs per kWh (c$/kWh)</th>
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<tbody>
<tr>
<td>SES</td>
<td>2.4 c$/kWh</td>
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<td>SOV</td>
<td>2.33 c$/kWh</td>
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<td>SOV &amp; Heli</td>
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</table>
Outcomes

- SOV, SOV & Heli, SES give the best solutions in terms of availability
- SES is the most suitable strategy
Atlantic & Gulf of Mexico;
Gemini (North Sea)

Repair Costs (M$/yr)

- New York: 21%
- Kitty Hawk: 20%
- Gulf of Mexico: 18%
Choice of the “most suitable” O&M Strategy

Repair Costs (M$/yr)

- New York: 13% (8%)
- Kitty Hawk: 19% (1%)
- Gulf of Mexico: 11.5% (6.5%)

Atlantic & Gulf of Mexico; Gemini (North Sea)
How to reduce the difference in repair costs?

In-house manufacturing of vessels

- Alternative to current strategy of chartering vessels from Europe
- No additional support vessel requirement to comply with Jones Act
- Overall lower vessel price and less mobilization time
Mid-Atlantic Gemini (North Sea)

Repair Costs (M$/yr)

~19% difference

Kitty Hawk
Mid-Atlantic; Gemini (North Sea)

Repair Costs (M$/yr)

Kitty Hawk

Gemini

-8%  19%
US offshore wind Challenges

Great Lakes

Pacific

Ice

Deep water

Atlantic & Gulf of Mexico

Hurricanes
Assumption: Hurricanes increase the failure rates of 20% of the most sensitive components

Components mainly affected by the hurricanes:

**Wind Turbine:**
- rotor blade
- blade adjustment
- turbine structure (tower)

**Balance Of Plant:**
- foundations
A challenge never experienced before:
Icing Conditions at the Lake Erie – 11 weeks per year.

*Impact of the Ice (in terms of availability)*

Without ice: ~ 95%
With ice: ~ 90%
Primary access vessel accessibility only possible under 10% ice coverage

Logistic solutions:
• Ice Breaker limitation on ice coverage 50%
• Helicopter as secondary access vessel
Outcomes

- Ice Breaking Vessel Availability: ~ +0%
- Helicopter Availability: ~ +3.2%
- CTV & Heli is the most suitable strategy
US offshore wind Challenges

- Atlantic & Gulf of Mexico
- Great Lakes
- Pacific
- Deep water
- Atlantic & Gulf of Mexico

Ice

Hurricanes

Map showing the locations of potential offshore wind challenges in the US.
Extremely Deep water Conditions

North Pacific
Logistic Solution:

Large replacements by the towing vessel and 2 support barges.

Outcomes:

- O&M Strategy with only SES and SOV possible
- SES gives lower availability (~93%)
- SOV is the most suitable strategy

Costs per kWh (c$/kWh):

- SES: 1.31 c$/kWh
- SOV: 1.31 c$/kWh
- SOV & Heli:

North Pacific
Outcomes

- CTV+, SES, SOV provide the highest availability
- CTV+ is the most suitable solution
“Each site needs a dedicated O&M strategy”
Leaders in O&M Modelling for offshore wind
Thank You!!!
Backup Slides
Wind Project Layout and Performance Modeling

Coverage includes:
- Major offshore areas except for Alaska
- Depths restricted up to 1,000 m to reflect limits of current technology

Wind project layout includes:
- One cell comprising 100 turbines
- Spacing based on 6-MW turbines in a 10-by-10 grid, spaced at 7 rotor diameters

Each project layout considered independently includes:
- 7,159 distinct wind power plant layouts*
- No gaps between adjacent layouts
- No wake interaction between layouts.

* A potential wind farm was considered to qualify if at least 50% of the turbines met the depth restriction criteria.
Model Outputs:

- The Energy Research Centre of the Netherlands (ECN) O&M Tool outputs are operational expenditures (OPEX), availability, and total O&M cost (OPEX + revenue loss).
- Parameterized curves fit to the ‘least cost O&M strategy’ at each distance (defined as O&M costs + lost revenue) for inclusion in the spatio-economic LCOE model.
## Strategy Optimization

### Summary:
For all the sites (possible)
1. CTV $\rightarrow$ 2
2. CTV A $\rightarrow$ 2
3. SES $\rightarrow$ 1
4. SOV $\rightarrow$ 1
5. CTV + Heli $\rightarrow$ 2
6. CTV A + Heli $\rightarrow$ 2
7. SOV + Heli $\rightarrow$ 1

**Using 1 SOV with 24 technicians!**

SOV can host up to 60 people, but in this study 24 technicians is used.

### Table:

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<thead>
<tr>
<th>Site</th>
<th>Name</th>
<th>STRATEGY</th>
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<tr>
<td>1</td>
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<td>2</td>
<td>Kitty Hawk</td>
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<td>3</td>
<td>Gulf of Mexico</td>
<td>DISTANCE - More than 4.5 hours travel</td>
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<tr>
<td>4</td>
<td>Lake Erie</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Pacific</td>
<td>DISTANCE &amp; Weather-More than 4.5 hours travel</td>
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<tr>
<td>6</td>
<td>Hawaii</td>
<td>3</td>
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</tbody>
</table>
Site 1: New York - Results

### Availability in time (%)

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Costs per kWh (c$/kWh)

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Costs per kWh (c$/kWh) O&M Strategy implemented

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Revenue Losses (M$/yr)

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Revenue Losses (M$/yr) O&M Strategy implemented

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Repair Costs (M$/yr)

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Repair Costs (M$/yr) O&M Strategy implemented

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Total effort (M$/yr)

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli

### Total effort (M$/yr) O&M Strategy implemented

- CTV
- CTV+
- SES
- SOV
- CTV & Heli
- CTV+ & Heli
- SOV & Heli
Site 2: Kitty Hawk - Results

- **Availability in time (%):**
  - SES: 93%
  - SOV: 94%
  - SOV & Heli: 95%

- **Availability in yield (%):**
  - SES: 93%
  - SOV: 94%
  - SOV & Heli: 95%

- **Costs per kWh (c$/kWh):**
  - SES: 49.5c$/kWh
  - SOV: 50c$/kWh
  - SOV & Heli: 50.5c$/kWh

- **Repair Costs (M$/yr):**
  - SES: 49.5M$
  - SOV: 50M$
  - SOV & Heli: 50.5M$

- **Revenue Losses (M$/yr):**
  - SES: 2M$
  - SOV: 2M$
  - SOV & Heli: 2M$

- **Total effort (M$/yr):**
  - SES: 50M$
  - SOV: 50M$
  - SOV & Heli: 50M$

O&M Strategy implemented
Site 3: Gulf of Mexico - Results

Availability in time (%)

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Availability in yield (%)

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Availability in yield (%)

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Costs per kWh (c$/kWh)

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Repair Costs (M$/yr)

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Revenu Losses (M$/yr)

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Total effort (M$/yr)

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Costs per kWh (c$/kWh) (O&M Strategy implemented)

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Revenu Losses (M$/yr) (O&M Strategy implemented)

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<tr>
<td>SES</td>
<td></td>
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<tr>
<td>SOV</td>
<td></td>
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</tr>
<tr>
<td>CTV+ &amp; Heli</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOV &amp; Heli</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Total effort (M$/yr) (O&M Strategy implemented)

<table>
<thead>
<tr>
<th></th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTV+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOV</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CTV+ &amp; Heli</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOV &amp; Heli</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Site 4: Lake Erie - Results

Availability in time (%)

Costs per kWh (c$/kWh)

Total effort (M$/yr)

O&M Strategy implemented
Site 5 – North Pacific - Results

### Availability in time (%)

- SES: 93%
- SOV: 96%
- SOV & Heli: 96%

### Costs per kWh (c$/kWh)

- SES: 1.25
- SOV: 1.3
- SOV & Heli: 1.35

### Total effort (M$/yr)

- SES: 45.5
- SOV: 46.5
- SOV & Heli: 53

Note: Costs per kWh and Total effort are calculated with O&M Strategy implemented.
### Site 6 - Hawaï

#### Availability in time (%)

<table>
<thead>
<tr>
<th>Option</th>
<th>Availability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTV</td>
<td>94</td>
</tr>
<tr>
<td>CTV+</td>
<td>94.5</td>
</tr>
<tr>
<td>SES</td>
<td>95</td>
</tr>
<tr>
<td>SOV</td>
<td>96</td>
</tr>
<tr>
<td>CTV &amp; Heli</td>
<td>96.5</td>
</tr>
<tr>
<td>CTV+ &amp; Heli</td>
<td>97</td>
</tr>
<tr>
<td>SOV &amp; Heli</td>
<td>96.5</td>
</tr>
</tbody>
</table>

#### Costs per kWh (c$/kWh)

<table>
<thead>
<tr>
<th>Option</th>
<th>Costs per kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTV</td>
<td>0.5</td>
</tr>
<tr>
<td>CTV+</td>
<td>1</td>
</tr>
<tr>
<td>SES</td>
<td>1.5</td>
</tr>
<tr>
<td>SOV</td>
<td>2</td>
</tr>
<tr>
<td>CTV &amp; Heli</td>
<td>1.5</td>
</tr>
<tr>
<td>CTV+ &amp; Heli</td>
<td>2</td>
</tr>
<tr>
<td>SOV &amp; Heli</td>
<td>2</td>
</tr>
</tbody>
</table>

#### Total effort (M$/yr)

<table>
<thead>
<tr>
<th>Option</th>
<th>Total effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTV</td>
<td>0</td>
</tr>
<tr>
<td>CTV+</td>
<td>0.5</td>
</tr>
<tr>
<td>SES</td>
<td>1</td>
</tr>
<tr>
<td>SOV</td>
<td>2</td>
</tr>
<tr>
<td>CTV &amp; Heli</td>
<td>2.5</td>
</tr>
<tr>
<td>CTV+ &amp; Heli</td>
<td>3</td>
</tr>
<tr>
<td>SOV &amp; Heli</td>
<td>3</td>
</tr>
</tbody>
</table>
• general trend: increase of the costs with the increase of failure rate:
  
  20% increase of failure rate $\rightarrow$ ~ 5% of the cost per kWh

• The variations of availability are not significant and are explained by the variation of the possibility of being in a given weather window depending on the simulation.
Assumption: The huge spare parts replacement vessels are assumed to be manufactured directly in US

- Daily price of Jack-up barge: 140 k$/day to 70 k $/day
- Mobilisation time 720 hours to 360 hours
- Mobilisation cost 1000 k$/mob to 750 k$/mob

Impact of Jones Act on O&M Costs – Vessels manufactured in US
# Impact of Jones Act on O&M Costs – Vessels manufactured in US – Mid Atlantic

<table>
<thead>
<tr>
<th></th>
<th>case control SOV</th>
<th>Removing of the US flag support barge+ decreasing the Jack-up barge daily price+ decreasing the mobilization time+decreasing the mobilization price</th>
<th>percentage difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability in time (%)</td>
<td>95.7</td>
<td>96</td>
<td>0.31</td>
</tr>
<tr>
<td>Availability in yield (%)</td>
<td>95.8</td>
<td>96</td>
<td>0.21</td>
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<tr>
<td>Costs per kWh (c$/kWh)</td>
<td>2.33</td>
<td>1.73</td>
<td>25.75</td>
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<tr>
<td>Repair Costs (M$/yr)</td>
<td>49.92</td>
<td>37.14</td>
<td>25.60</td>
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<tr>
<td>Revenu Losses (M$/yr)</td>
<td>4.01</td>
<td>3.77</td>
<td>5.99</td>
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<tr>
<td>Total effort (M$/yr)</td>
<td>53.93</td>
<td>40.92</td>
<td>24.12</td>
</tr>
</tbody>
</table>
## Gemini and New York Comparisons

### Site 1 New York
- Distance to shore: 70 km
- Depth: 30 m

<table>
<thead>
<tr>
<th>SITE 1 NEW YORK</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Wind Speed (m/s)</td>
<td>7.06</td>
</tr>
<tr>
<td>Wave height (m)</td>
<td>1.27</td>
</tr>
</tbody>
</table>

### Gemini
- Distance to shore: 85 km
- Depth: 30 - 35 m

<table>
<thead>
<tr>
<th>EUROPE : GEMINI</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
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<tr>
<td>Wind Speed (m/s)</td>
<td>7.63</td>
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<tr>
<td>Wave height (m)</td>
<td>1.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CTV</th>
<th>CTV +</th>
<th>Surface Effect Ship</th>
<th>Service Operating Vessel</th>
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</thead>
<tbody>
<tr>
<td>0.69</td>
<td>0.85</td>
<td>0.93</td>
<td>0.96</td>
</tr>
<tr>
<td>CTV</td>
<td>CTV +</td>
<td>Service Operating Vessel</td>
<td></td>
</tr>
<tr>
<td>0.57</td>
<td>0.74</td>
<td>0.84</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Gemini and New York Comparisons

Site 1 New York Lease Area
Distance to shore: 70 km
Depth: 30 m

Gemini
Distance to shore: 85 km
Depth: 30 - 35 m
Gemini and New York Comparisons

Site 1 New York Lease Area
Distance to shore: 70 km
Depth: 30 m

Gemini
Distance to shore: 85 km
Depth: 30 - 35 m
Gemini and New York Comparisons

**Availability in time (%)**

- Gemini: 94.5%
- New York: 95.5%

**Availability in yield (%)**

- Gemini: 94.5%
- New York: 95.5%

**Costs per kWh (c$/kWh)**

- Gemini: 0.94
- New York: 0.95

**Revenue Losses (M$/yr)**

- Gemini: 12.2
- New York: 10.5

**O&M Strategy implemented**

- Repair Costs (M$/yr)
  - Gemini: 52
  - New York: 54

- Total effort (M$/yr)
  - Gemini: 93
  - New York: 95