Renewable Energy and Inter-island Power Transmission

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
NREL’s Role in Variable Renewable Energy Integration

- Integration studies and operational impacts;
- Wind/solar plant modeling and interconnection;
- Transmission planning and analysis;
- Resource assessment and forecasting.

Energy Development for Island Nations (EDIN)
- U.S. Virgin Islands (reduce dependency on fossil fuel by 60% by 2025).
- Iceland and Dominica collaboration.
- Pacific Islands.

Wind/PV/Energy storage projects in Hawaii.
Overview

- Submarine Power Transmission Technologies.
- Hawaii Wind Integration and Transmission Study.
- Caribbean Work.
HVAC vs. HVDC

Breakeven distance
400-700 km overhead
50-100+ km submarine
Advantages

- Long distance transmission with lower costs and losses;
- No high capacitance effect on DC (no reactive losses);
- More power per conductor, no skin effect, 2 conductors only;
- Connecting unsynchronized grids, rapid power flow control;
- Buffer for some disturbances, stabilization of power flows;
- Multi-terminal operation;
- Good for weaker grids;
- Helps integrating large amount of variable generation.

Disadvantages

- High cost of power converters;
- Complexity of control, communications, etc.;
- Maintenance cost higher than for AC, spare parts needed;
- HVDC circuit breaker reliability issue.
HVDC Technologies

HVDC Classic – LCC Converters (bipole shown)

HVDC VSC Technology (bipole shown)
HVDC Configurations

Monopolar Link

Bipolar Link

Multi-Terminal Configuration
Submarine Cables - How Deep?

- The current experience is limited to water depths up to 1620 m;
- HVDC ultra-deep technology up to 2000 m possible – no experience so far;
- Based on published literature, 80 kVDC / 100 MW is possible even at 2200 m;
- Additional development and testing including full-scale sea trial is needed for higher depths.
Oahu Wind Integration and Transmission Study (OWITS)

Hawaii Clean Energy Initiative (HCEI) – October 2008
- Multi-year initiative;
- 70% clean energy by 2030 (40% by renewables);
- Agreement between state of Hawaii and HECO:
  • 400 MW of wind from Lanai and/or Molokai to Oahu (Stage 1);
  • 200 MW of wind from Maui to Oahu (Stage 2).

OWITS Study
- Support to HCEI and HECO;
- FY 09/10;
- TRC consists of regional, national, and international experts;
- TRC held 5 in-person meetings;
- Reviewed and provided feedback on study methods, data needs, and results.
## Big Wind Scenarios for HCEI (Stage 1)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Wind (MW)</th>
<th>Solar (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oahu</td>
<td>Lanai</td>
</tr>
<tr>
<td>1. Oahu Wind</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2. Off-island Wind</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3. Concentrated Wind</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>4. Oahu Solar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. High Renewables</td>
<td>100</td>
<td>200</td>
</tr>
</tbody>
</table>

Stage 2 includes interconnection to Maui.
OWITS Cable Study Inputs

- Potential cable landing points and inter-island routes have been identified in Ocean Floor Survey Report (DBEDT);
- Maximum water depth – around 800 m;
- Sending and receiving end voltages – 138 kV;
- PSSE load flow data from HECO;
- Contract between NREL and Electranix for transmission modeling.
18 options analyzed (AC, DC, or combination of both).

<table>
<thead>
<tr>
<th>Stage 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only 6 selected for detailed simulation (AC and DC).</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only 3 final scenarios (including interconnections to Maui) selected for further detailed dynamic simulation.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs (HVAC)</th>
<th>Costs (HVDC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Cables</td>
<td>DC Cables</td>
</tr>
<tr>
<td>AC substations</td>
<td>DC converter stations</td>
</tr>
<tr>
<td>Sea/land cable transition</td>
<td>Sea/land cable transition</td>
</tr>
<tr>
<td>Fixed compensation reactors</td>
<td>-</td>
</tr>
<tr>
<td>Other components</td>
<td>Other components</td>
</tr>
<tr>
<td>AC losses (20 years)</td>
<td>DC losses (20 years)</td>
</tr>
<tr>
<td><strong>Total HVAC cost</strong></td>
<td><strong>Total HVDC cost</strong></td>
</tr>
</tbody>
</table>

RFQ
• Simulations were conducted for worst case contingencies.

• 230 kV / 3-core cable.

• AC solution will work without SVC or STATCOM enhancements (100% shunt compensation is required).

• Depths may represent challenges for 3-core AC cables.
<table>
<thead>
<tr>
<th>HVDC Option C3-2</th>
<th>HVDC Option A3-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram C3-2" /></td>
<td><img src="image2" alt="Diagram A3-2" /></td>
</tr>
<tr>
<td><strong>HVDC Option B3-2</strong></td>
<td><strong>HVDC Option C1-2</strong></td>
</tr>
<tr>
<td><img src="image3" alt="Diagram B3-2" /></td>
<td><img src="image4" alt="Diagram C1-2" /></td>
</tr>
<tr>
<td><strong>HVDC Option B1-2</strong></td>
<td><strong>HVDC Option A1-2</strong></td>
</tr>
<tr>
<td><img src="image5" alt="Diagram B1-2" /></td>
<td><img src="image6" alt="Diagram A1-2" /></td>
</tr>
</tbody>
</table>
Range for Budgetary Capital costs for HVDC options (including burial and termination)

<table>
<thead>
<tr>
<th>Option Description</th>
<th>C3-2</th>
<th>A3-2</th>
<th>A1-2</th>
<th>B3-2</th>
<th>C1-2</th>
<th>B1-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter Stations $M</td>
<td>234</td>
<td>288</td>
<td>414</td>
<td>234</td>
<td>288</td>
<td>288</td>
</tr>
<tr>
<td>DC Cables $M</td>
<td>154</td>
<td>180</td>
<td>367</td>
<td>221</td>
<td>216</td>
<td>245</td>
</tr>
<tr>
<td>Total Stage 1 Price $M</td>
<td>388</td>
<td>468</td>
<td>781</td>
<td>455</td>
<td>504</td>
<td>533</td>
</tr>
<tr>
<td>Stage 2 Maui to Oahu (Approx)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Converter Stations $M</td>
<td>144</td>
<td>144</td>
<td>117</td>
<td>144</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>DC Cables $M</td>
<td>420</td>
<td>420</td>
<td>192</td>
<td>283</td>
<td>272</td>
<td>272</td>
</tr>
<tr>
<td>Total Stage 2 Price $M</td>
<td>564</td>
<td>564</td>
<td>309</td>
<td>427</td>
<td>416</td>
<td>416</td>
</tr>
<tr>
<td>Total Stages 1 &amp; 2 $M</td>
<td>951</td>
<td>1,032</td>
<td>1,090</td>
<td>882</td>
<td>920</td>
<td>949</td>
</tr>
</tbody>
</table>

OWITS Final Scenario 1

- 400-MW bipole VCS link between Molokai and Oahu.
- AC cable between Molokai and Lanai.
OWITS Final Scenario 2

- 200-MW monopole VCS link between Molokai and Oahu.
- 200-MW monopole VCS link between Molokai and Lanai.
- AC cable between Molokai, Lanai, and Maui.
OWITS Final Scenario 3

- 400-MW bipole VCS link between Molokai and Oahu.
- AC cable between Molokai, Lanai, and Maui.
• Strategies were developed to enhance integration of renewables for each scenario:
  • Wind power forecasting to improve commitment;
  • Refining the up-reserve requirements by using fast start units and load control;
  • Reducing minimum power of the baseload units;
  • Seasonally cycling off some selected baseload units; Increasing the thermal unit ramp-rate capability and enhancing the droop;
  • Considering advanced wind turbine technologies (inertia and frequency control);
  • Some aspects of short-term storage were examined for implementing ramp rate limits of wind plants.

• Adequate reserve requirements for sustained drops in wind over an hour;

• The largest drop in wind and solar power over 10-min. periods can be handled with future improved AGC ramp rates;

• Quick variations in wind and solar (1 to 5 min. time frame) might require short-term storage for up/down ramp rate limiting;

• Detailed transient modeling to evaluate the system’s response to worst case contingences (voltage faults at different locations) was conducted;

• PPAs were signed between HECO and Castle & Cook ($0.11 to 0.13/kWh plus transmission costs).
On-going Puerto Rico – USVI: BVI Interconnection Study

- DOE funded project
- Participants:
  - NREL
  - VI WAPA
  - PREPA / IAES
  - Siemens

The study is focused on options for:
- 50-mile interconnection between PR and STT;
- 10-mile interconnection between STT and BVI;
- 80+ mile interconnection between STT and STX; or
- Direct interconnection between PR and STX as an alternative.
PR-USVI Bathymetry

NREL-developed map. Combination of 10, 30, and 100-m horizontal resolution, and based on NOAA data.
Puerto Rico – USVI Bathymetry

NREL-developed map. Combination of 10, 30, and 100-m horizontal resolution, and based on NOAA data.
Puerto Rico – USVI: BVI Interconnection Study Objectives

- Determine power capacities, types, and requirements of the three interconnections;
- Perform power system study and identify necessary infrastructure reinforcements;
- Demonstrate potential benefits (generation costs, reliability, etc.);
- Estimate project costs.

Project Timeline
- October 2010 – Project kickoff
  - January 2010 – Interim report #1
    - HVAC/HVDC requirement
    - Submarine cable study
  - April 2011 – Interim report #2
    - Power system study
  - July 2011 – Final report.

Example of AC and DC Interconnection option

NREL developed map.
Adding 30 MW of Wind (Extreme Scenario)

- Baseload for combustion generation reduced to 20 MW;
- 60 MW of variable load;
- No day/night peaks;
- Big change in power system operation.
How PREPA Interconnection Can Help?

- PREPA can provide both base load and/or regulation power to WAPA.
- Different energy cost structure may be associated with each service.
PV Variability Will Contribute to Regulation Requirements

Fluctuations of 1min PV Output - Example

Ideal

Cloud Impact

kW/min

TIME (HR)

POWER (kW)

2.5-MW PV, measured in Las Vegas, NV area

Single-axis tracking
Submarine Interconnection Can Help with Fast Regulation

- PREPA maintains large reserve capacity for Automatic Generation Control (AGC).
- Faster (sub-second) power control is possible with HVDC option (built-in feature).
- Voltage control simultaneous with power control.
• Short self-recovering faults will create voltage dips in WAPA system (AC link);
• May be a serious reliability issue during times of large power imports;
• Wind power low voltage ride-through (LVRT) capability is essential for reliable operation;
• Overall LVRT capability of WAPA system can be improved by FACTS in case of HVAC interconnection;
• Modeling is necessary for various contingency scenarios, target penetration levels and wind turbine topologies, etc.
Larger Regional Interconnection

USVI Benefits:
• Diversified supply of energy;
• Clean baseload geothermal power from St. Kitts/Nevis;
• LNG-generated power from PR;
• Higher reliability;
• Lower energy costs.

NREL developed map. Cable routes are notional.
Caribbean Power Interconnection and Renewable Energy

- The energy solutions for the Caribbean region include new fuels (e.g., LNG), new energy resources, and electrical interconnections between islands;
- Geothermal power is considered as a main driver for the interconnection;
- Caribbean wind energy (estimated at 3.7 GW) as a driver for interconnection?
- Variability of wind power represents significant challenges compared to baseload geothermal power.
Areas 1, 2, and 3 – may have gaps deeper than 1650 m.
Caribbean Bathymetry and Slopes

Depths less than 2000 m and slopes less than 20°

NREL-developed map, 1-km horizontal resolution, based on GEBCO data.
Potential Benefits of Regional Interconnections in Caribbean

- Deliver lower cost electrical power from the island (or country) that has such power to an island (or country) that does not;

- Possibility of transmitting large amounts of electrical energy generated by renewable sources;

- Increased reliability, reduced spinning reserve requirements, and shared frequency regulation without adding new generation;

- Increase the potential for high-penetration variable renewable generation;

- Reduce dependence on high price imported oil and increase high level utilization of renewable energy sources on the regional level;

- Integrating fiber-optic communication cables.
Thank you!