High Voltage Direct Current
And Large Scale Wind Integration

Iowa State University
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Wayne Galli, Ph.D., P.E.
Executive Vice President – Transmission and Technical Services
Clean Line Energy Partners
Focus, team and capital to connect renewable energy to demand

• Clean Line Energy develops long-haul, high-voltage direct current ("HVDC") transmission lines to connect the best wind resources in North America to communities that lack access to low-cost renewable power

• HVDC is the lowest cost, least land intensive, most reliable transmission technology to integrate large amounts of renewable energy

• Clean Line’s management team brings a track record of success in energy project development

• Supported by investors who bring long-term perspective, patient capital and an understanding of siting and building interstate infrastructure projects
North American Grid 230 kV and above
3 Major Interconnections, 8 Regions
3 Major Interconnections, 8 Regions, 135 Balancing Authorities
Topics

• The challenge & our solution

• Wind costs

• Project development approach

• Wind Integration
The best wind resources are located far from load centers and the existing grid infrastructure.
It is makes sense to build where it is windy... trends are downward.

Map shows generation-weighted average levelized wind power purchase agreement (PPA) prices by region for PPAs signed in 2011 and 2012 (in $/MWh).

Clean Line’s projects connect the best wind resources to demand centers
Transmission is being built to meet state and regional needs, but need for interregional transmission remains.
HVDC transmission lines bring economic, environmental and electric reliability benefits

More Efficient – Over long distances, transfer power with less infrastructure and lower line loss than AC lines moving a comparable amount of power

Lower Cost – Require less infrastructure and have lower line losses, resulting in lower costs and lower prices for renewable energy

Improved Reliability – Give operator complete control over power flow and facilitate the integration of wind energy from different resource areas

Smaller Footprint – Use narrower right-of-way than comparable AC lines

Merchant model – Clean Line will fund the costs of the transmission projects and sell transmission capacity to wind generators and load serving entities

**AC** 3000-4000 MW Capacity **DC**

Three 500 kV lines 600 foot ROW

One ± 500 kV bipole 150-200 foot ROW
Over time DC applications have gained popularity across North America for appropriate applications…
Though the grid is mostly AC, there are many recently proposed North American HVDC projects.
...and more recently HVDC has experienced a Renaissance internationally (especially in China)
Cost vs. Distance: when long distance makes sense
Line Loadability vs. Distance

Assuming 345 kV AC lines, you’d need at least 7 circuits to deliver the power. Line losses are 470 MW.
Let’s beef up the AC lines

If you series compensate those 345 kV AC lines, you need a minimum of three circuits. Losses are huge... 1200MW
What happens if you lose one of those lines?

The remaining lines are overloaded, voltage collapse ensues
3500 MW of wind power is delivered from Iowa to Illinois via a 600 kV DC line. Line losses amount to 90 MW.
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Improving wind turbine technology is increasing capacity factors and reducing wind costs

**Improving GE 1.5-1.7 MW Turbine from 2005 – 2012**

*Net Capacity Factor*¹
At 8.5 meters per second average 80 m wind speed site

In meters

<table>
<thead>
<tr>
<th>Rotor Diameter</th>
<th>77</th>
<th>82.5</th>
<th>100</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub Height</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>100</td>
</tr>
</tbody>
</table>

1. Assumptions: shear alpha = 0.2, Rayleigh distribution, 17% losses from GCF to NCF
High capacity factor wind is competitive with other sources of new generation

Levelized Cost of Energy

Wind and gas are low cost choices

Expensive sources of fuel diversity

<table>
<thead>
<tr>
<th>Renewable generation source</th>
<th>Non-renewable generation source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind with the PTC</td>
<td>Wind without the PTC</td>
</tr>
<tr>
<td>Combined Cycle Gas Turbine</td>
<td>Solar PV Thin-Film</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Coal</td>
</tr>
<tr>
<td>IGCC</td>
<td>Solar Thermal</td>
</tr>
</tbody>
</table>

1. Cost of generation based on mid-point of Lazard’s LCOE estimates. Unless noted, costs shown are unsubsidized.
2. High capacity factor wind cost uses low-end Lazard estimates for which the capacity factor is 52% and capex cost is $1,500/kW.
3. Assumes $4.50/MMBtu gas price.

Source: Lazard’s 2013 Levelized Cost of Energy Analysis

CLEAN LINE ENERGY PARTNERS
Impending carbon regulation makes low-cost wind energy even more valuable

Expected timeline of EPA rules on carbon emissions from existing power plants under §111(d) of the Clean Air Act

- **2014**
  - Proposed Rule due

- **2015**
  - Rule finalized

- **2016**
  - Legal challenges completed, state implementation plans due

- **2016-2017**
  - Rule is effective

• In June 2013, President Obama directed the EPA to implement new source §111(b) and existing source §111(d) rules of the Clean Air Act by June 2016
• EPA proposed Carbon Pollution Standard for New Power Plants under §111(b) in Sep. 2013
• Proposal for existing source limits will be issued in 2014
• Tradeable carbon allowances are a possible implementation method
Topics

• The challenge & our solution
• Wind costs

• **Project development approach**

• Wind Integration
Interregional project development requires multi-faceted approach
There is no replacement for shoe leather and one-on-one conversations

- Pre-siting county meetings
- Pre-design agency and NGO workshops
- County Roundtable Workshops
- Local Business Opportunity Meetings
- Public Open Houses
Clean Line’s Projects deliver to three markets, demand drivers are unique to each market
RPS Demand in PJM will create need for new transmission

RPS Demand in PJM States

Projected demand

Current supply + Rock Island or Grain Belt

Current supply (in PJM states, 2013 YE installed capacity)
Clean Line Projects’ endpoints also each have unique interconnection processes
Technical Challenges...some of what keeps my life interesting

- Integrating large amounts of wind using HVDC Classic has inherent challenges, but is a natural progression in the use of HVDC
  - Need for optimized reactive power control scheme
  - Operating with low short circuit levels
  - Lack of significant inertia associated with wind generation
  - Need for fast communication between HVDC and wind park controllers
Project Specific Engineering Challenges

- Transient over-voltages
- Frequency deviations
- Stable DC power recovery
- Active power exchange with AC rectifier network
- Control Coordination
Topics

- The Challenge & our solution
- Wind costs
- Project development approach
- **Wind Integration**
Over small time intervals, wind has low variability

Standard deviation of step-changes
MW vs. Time Interval (minutes)

Automatic Generation Control
Fast Response Units
Most remaining units

Source: 2011 output from Buffalo Gap 2 Wind farm (230 MW near Abilene, TX)
Geographically diverse wind portfolio makes wind integration easier

<table>
<thead>
<tr>
<th></th>
<th>KS</th>
<th>IA</th>
<th>IL</th>
<th>IN</th>
<th>PA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KS</strong></td>
<td></td>
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<tr>
<td><strong>IA</strong></td>
<td>0.37</td>
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<tr>
<td><strong>IL</strong></td>
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<tr>
<td><strong>IN</strong></td>
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<tr>
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<td>0.00</td>
<td>0.02</td>
<td>0.15</td>
<td>0.19</td>
<td></td>
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</tbody>
</table>

- **Low correlation**: between 0.0 and 0.25
- **Medium correlation**: between 0.25 and 0.5
- **High correlation**: between 0.5 and 1.0

Source: EWITS; Clean Line analysis

1. “Low correlation”: between 0.0 and 0.25; “Medium correlation”: between 0.25 and 0.5; “High correlation”: between 0.5 and 1.0
Integrating wind does not require large increases in operating reserves

AWS Truepower performed a net load analysis to estimate the increase in operating reserves needed to integrate 3500 MW of wind energy into the TVA and surrounding systems. The table below shows the results for 1) all 3500 MW absorbed by TVA and 2) 1750 MW absorbed by TVA and the rest delivered to neighbors.

<table>
<thead>
<tr>
<th>Incremental Three-Sigma Variation of Net Load Scenarios</th>
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<tbody>
<tr>
<td>3500 MW All TVA</td>
</tr>
<tr>
<td>TVA</td>
</tr>
<tr>
<td>Southern</td>
</tr>
<tr>
<td>Duke</td>
</tr>
<tr>
<td>Entergy</td>
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<tr>
<td>Total</td>
</tr>
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</table>
No more energy only - many methodologies exist to calculate the capacity value of wind

<table>
<thead>
<tr>
<th>Method</th>
<th>Who does it this way</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective load carrying capacity (ELCC)</td>
<td>MISO, ERCOT, Northern States Power Co. (Xcel), Public Service Company of Colorado, PacifiCorp, Puget Sound Energy</td>
</tr>
<tr>
<td>Peak period contribution</td>
<td>TVA, PJM, SPP</td>
</tr>
<tr>
<td>Percentage of capacity factor or nameplate capacity</td>
<td>NYISO, Public Service of New Mexico, Arizona Public Service, Portland General Electric, Idaho Power, Dominion, Entergy</td>
</tr>
</tbody>
</table>
Thank you .... QUESTIONS?