The Latest in Wind and Solar Technologies

Implications for the Power System

Presentation to the
Colorado Renewable Energy Society

David Mooney

January 16, 2018
Outline

• Global Renewable Energy Markets Update
• Technology Overviews
  ➢ Wind and Solar
    ✧ Market Segments
    ✧ Global and US Markets
    ✧ Cost Trends
    ✧ Status in Colorado
• Power Systems Research – High Wind and Solar Penetrations
• Trends in Storage
Outline

• Global Renewable Energy Markets Update
  • Technology Overviews
    ➢ Wind and Solar
    ✦ Market Segments
    ✦ Global and US Markets
    ✦ Cost Trends
    ✦ Status in Colorado
  • Power Systems Research – High Wind and Solar Penetrations
  • Trends in Storage
Global Renewable Energy Capacity

- Total global electricity gen capacity - ~6,000 GW
- Non-hydro renewables ~15% of total
- All RE - >30% of total installed capacity

Source: NREL RE Data Book
Global Installed Renewable Capacity - 2016

Source: NREL RE Databook, REN21
Outline

• Global Renewable Energy Markets Update
• Technology Overviews
  ➢ Wind and Solar
    ✷ Market Segments
    ✷ Global and US Markets
    ✷ Cost Trends
    ✷ Status in Colorado
• Power Systems Research – High Wind and Solar Penetrations
• Trends in Storage
Wind Energy

Gansu Wind Farm
Gansu, China
8 GW (going to 20 GW)
Westermeerwind Wind Farm
• Noordoostpolder, Netherlands
• 144 MW

Horn Rev Wind Farm
• West coast of Denmark
• 160 MW
Wind Energy - Onshore

Peetz Table Wind Energy Center
• Peetz, Colorado
• 575 MW

Cedar Creek Wind Farm
• Grover, Colorado
• 550 MW
Global Wind Markets - 2016

Global Installed Capacity – 487 GW
Offshore – 14 GW
U.S. Wind Market

Colorado Rank – 10
Under Construction – 76 MW
Technical Potential – ~270,000 MW
Colorado Wind Development

**Wind Projects**
- Installed wind capacity: 3,029 MW
- State rank for installed wind capacity: 10th
- Number of wind turbines: 1,913
- State rank for number of wind turbines: 8th
- Wind projects online: 25 (Projects above 10 MW: 17)
- Wind capacity under construction: 76 MW
- Wind capacity in advanced development: 600 MW

**Current Wind Generation**
During 2016, wind energy provided 17.33% of all in-state electricity production.
- Equivalent number of homes powered by wind: 871,000

**Wind Generation Potential**
The DOE Wind Vision Scenario projects that Colorado could produce enough wind energy by 2030 to power the equivalent of 670,000 average American homes.
- Land based technical wind potential at 80 m hub height: 274,353 MW
- Land based technical wind potential at 110 m hub height: 262,878 MW (Source: NREL)

**Environmental Benefits**
Generating wind power creates no emissions and uses virtually no water.
- 2016 annual state water consumption savings*: 5.0 billion gallons
- 2016 equivalent number of water bottles saved: 38.2 billion
- 2016 annual state carbon dioxide (CO₂) emissions avoided: 9.3 million metric tons
- 2016 equivalent cars worth of emissions avoided: 2.0 million

*Based on national average water consumption factors for coal and gas plants

Source: AWEA
U.S. Wind Market Growth (Through Q3 2017)

~85 GW
Colored bars illustrate range across all representative plants in the ATB. Black bars illustrate the representative ATB plant characteristics that align with the type of plant that would likely be built in today’s market.
Outline

- Global Renewable Energy Markets Update
- Technology Overviews
  - Wind and Solar
    - Market Segments
    - Global and US Markets
    - Cost Trends
    - Status in Colorado
- Power Systems Research – High Wind and Solar Penetrations
- Trends in Storage
Golmud Solar Park, Western China – 200 MW
PV Markets – Residential
PV Markets – Utility
Desert Sunlight Solar Farm

- NextEra Energy
- 8.8 million First Solar CdTe panels
- 550 Mwac
- 300,000 tons CO2 displaced
- 6.2 square miles
- End-to-end – 6,600 miles
PV Markets – Utility

**Solar Star**
- BHE Renewables
- 1.7 million SunPower c-Si panels
- 579 Mwac
- 300,000 tons CO2 displaced
- 5 square miles
- End-to-end – 1,650 miles
Global Solar Energy Markets - 2016

- United Kingdom: 11.1 GW
- France: 7.2 GW
- Spain: 7.8 GW
- United States: 42.4 GW
- Germany: 41.2 GW
- Italy: 19.3 GW
- India: 9.5 GW
- China: 78.0 GW
- Japan: 43.0 GW
- Australia: 6.0 GW

Sources: REN21, SEIA/GTM
Includes CSP and grid-connected PV; capacity is reported in MWac.
U.S. Solar Deployment (2016)

Sources: NREL RE Databook, GTM/SEIA and IREC

PV Cumulative Capacity\(^1\) (MW)

<table>
<thead>
<tr>
<th>Rank</th>
<th>State</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>California</td>
<td>17,084</td>
</tr>
<tr>
<td>2</td>
<td>North Carolina</td>
<td>3,016</td>
</tr>
<tr>
<td>3</td>
<td>Arizona</td>
<td>2,700</td>
</tr>
<tr>
<td>4</td>
<td>Nevada</td>
<td>2,017</td>
</tr>
<tr>
<td>5</td>
<td>New Jersey</td>
<td>1,991</td>
</tr>
<tr>
<td>6</td>
<td>Utah</td>
<td>1,489</td>
</tr>
<tr>
<td>7</td>
<td>Massachusetts</td>
<td>1,487</td>
</tr>
<tr>
<td>8</td>
<td>Georgia</td>
<td>1,432</td>
</tr>
<tr>
<td>9</td>
<td>Texas</td>
<td>1,215</td>
</tr>
<tr>
<td>10</td>
<td>New York</td>
<td>927</td>
</tr>
</tbody>
</table>

PV Annual Capacity\(^1\) Additions (MW)

<table>
<thead>
<tr>
<th>Rank</th>
<th>State</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>California</td>
<td>5,096</td>
</tr>
<tr>
<td>2</td>
<td>Utah</td>
<td>1,241</td>
</tr>
<tr>
<td>3</td>
<td>Georgia</td>
<td>1,023</td>
</tr>
<tr>
<td>4</td>
<td>Nevada</td>
<td>984</td>
</tr>
<tr>
<td>5</td>
<td>North Carolina</td>
<td>923</td>
</tr>
<tr>
<td>6</td>
<td>Texas</td>
<td>672</td>
</tr>
<tr>
<td>7</td>
<td>Arizona</td>
<td>657</td>
</tr>
<tr>
<td>8</td>
<td>Massachusetts</td>
<td>406</td>
</tr>
<tr>
<td>9</td>
<td>Florida</td>
<td>404</td>
</tr>
<tr>
<td>10</td>
<td>Colorado</td>
<td>382</td>
</tr>
</tbody>
</table>

CSP Cumulative Capacity\(^2\) (MW)

<table>
<thead>
<tr>
<th>Rank</th>
<th>State</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>California</td>
<td>1,256</td>
</tr>
<tr>
<td>2</td>
<td>Arizona</td>
<td>283</td>
</tr>
<tr>
<td>3</td>
<td>Nevada</td>
<td>174</td>
</tr>
<tr>
<td>4</td>
<td>Florida</td>
<td>75</td>
</tr>
<tr>
<td>5</td>
<td>Hawaii</td>
<td>7</td>
</tr>
</tbody>
</table>

Sources: NREL RE Databook, GTM/SEIA and IREC
Trends in PV Power

U.S. Total – 42,447 MW

Annual MW

Utility
Commercial
Residential
Utility $/W


0 1,000 2,000 3,000 4,000 5,000 6,000 7,000 8,000 9,000 10,000 11,000 12,000 13,000 14,000 15,000 16,000

$- $0.50 $1.00 $1.50 $2.00 $2.50 $3.00 $3.50 $4.00

NATIONAL RENEWABLE ENERGY LABORATORY

24
Colorado PV Market

Colorado Total – 925 MW

Colorado Rank – 10

Technical Potential
PV – 4,500 GW
CSP – 3,100 GW

Utility
Commercial
Residential
Colorado Solar Development

• As of 2016, **410 solar companies** throughout the value chain in Colorado, **employing over 8,000 people.**
• In 2016, Colorado **installed 382 MW of PV,** ranking it 10th nationally.
• Total installed capacity – **925 MW.** There is enough solar energy installed in the state to **power 186,000 homes.**
• $2.7B invested in Colorado solar to date. ($510M in 2016).
• Average installed residential and commercial photovoltaic system **prices in Colorado have fallen by 64% in the last five years.**
Outline

• Global Renewable Energy Markets Update
• Technology Overviews
  ➢ Wind and Solar
    ✧ Market Segments
    ✧ Global and US Markets
    ✧ Cost Trends
    ✧ Status in Colorado
• Power Systems Research – High Wind and Solar Penetrations
• Trends in Storage
Trends in the U.S. Power System

Source: EIA – Electric Power Annual
SEAC Electricity Modeling at Multiple Scales

IAMs, CGEs
Global
SolarDS
Rooftop PV adoption

Global energy-economic-climate

U.S.
ReEDS
National policy, market, technology analysis

Regional/Balancing Area

Regional integrated resource planning

Agent Based Models of Customer Behavior

Generator

Annual Seasonal/Diurnal Hourly Sub-hourly

Temporal Resolution

System Models

Production Cost / Grid Simulation Models

Security-constrained unit commitment & economic dispatch

Automatic generation control (AGC) & dispatch

Hourly plant output

Sub-hourly

Solar resource
Thermal generation
Wind resource
Load
Hydro
Transmission
Fuel prices

NATIONAL RENEWABLE ENERGY LABORATORY
What does ReEDS do?

ReEDS generates scenarios of the future U.S. power system.

ReEDS finds the regional mix of technologies that meet requirements of the electric sector at least cost.
What are the key outputs?

Capacity and generation evolution of all generator types

Wind Vision: A New Era for Wind Power (DOE 2015)
EI- The Largest Coordinated Power System in the World

Eastern Interconnection
2010 base transmission network
EI - Reliably Designed for Traditional Fuel Sources
EI- Now a System in Transition

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. Billy Roberts, 2015 May 05

Coal  Nuclear  Hydro  Combustion Turbine (Natural Gas)  Combined Cycle (Natural Gas)
EI Profile

- Generating capacity: 700 GW
- Generating units: 7,500
- Load: 3,000 TWh
- Population: 240 million people
- 70% of US Load
- Transmission length: 459,000 miles
- Nodes: 60,000
- Transmission lines: 50,000

Question: What combination of generators and transmission pathways serves the load at each node for the least cost?
A Unit Commitment Problem

• Minimize operating costs according to constraints:
  – Transmission
  – On/Off decisions
  – Ramp constraints
  – Reserves
  – Emissions

• Tens of millions of equations for every day
  o 50,000 nodes
  o 60,000 transmission lines
  o 5,600 generators
  o 8,760 days

• Economic Dispatch
  o Similar formula for 105,120, 5-minute intervals

\[
\begin{align*}
\min & \sum_t \sum_g (c_g P_{g,t} + c_g^u s_{g,t}) \\
\text{s.t.} & \quad \theta_n^{\text{min}} \leq \theta_{n,t} \leq \theta_n^{\text{max}}, \quad \forall n, t \\
& \quad p_g^{\text{min}} u_{g,t} \leq P_{g,t} \leq p_g^{\text{max}} u_{g,t}, \quad \forall g, t \\
& \quad p_k^{\text{min}} \leq P_{k,t} \leq p_k^{\text{max}}, \quad \forall k, t \\
& \quad \sum_{i=n} P_{kij,t} - \sum_{j=n} P_{kij,t} - \sum_g P_{ng,t} - \sum_d P_{nd,t} = 0, \forall n, t \\
& \quad B_k(\theta_n - \theta_m) - P_{k,t} = 0, \quad \forall k, t \\
& \quad s_{g,t} - x_{g,t} = u_{g,t} - u_{g,t-1}, \quad \forall g, t \\
& \quad s_{g,t} \leq 1 - u_{g,t-1}, \quad \forall g, t \\
& \quad x_{g,t} \leq u_{g,t-1}, \quad \forall g, t \\
& \quad u_{g,t} \in \{0, 1\} \quad \forall g, t \\
& \quad x_{g,t} \in \{0, 1\} \quad \forall g, t \\
& \quad s_{g,t} \in \{0, 1\} \quad \forall g, t
\end{align*}
\]

CHALLENGE: Solve for the least cost dispatch over 105,000 times for each scenario.
1 partition: estimated solve time 545 days
Simulation Time Comparison

1 partition: estimated solve time 545 days

12 partitions: estimated solve time 60 days

73 partitions: actual solve time 19 days
• Video removed due to size
• For a variety of data visualizations, visit

https://www.youtube.com/user/NRELLearn/feed
Projects that Work Toward Our 2050 Goal: Reliable, Affordable, Clean Power for North America

- **Interconnections Seam Study**
  - What happens if the east joins the west?
  - March 2018

- **North American Renewable Integration Study**
  - What if North America works together?
  - October 2019

- **Electrification Futures Study**
  - What if the energy economy electrifies?
  - October 2019

- **Multi-scale Production Cost Modeling (70% VRE)**
  - Can we make models more detailed and faster?
  - October 2018

- **Los Angeles 100%**
  - Can LA operate on 100% Renewable Energy
  - July 2020
The U.S. has Diverse Resources and Demand
The U.S. has Diverse Resources and Demand
The U.S. has Diverse Resources and Demand

Major US Fossil Resource Plays
The U.S. has Diverse Resources and Demand
The U.S. has Diverse Resources and Demand
The U.S. has Diverse Resources and Demand
The East/West Seam

US Transmission System and B2B HVDC Ties

- Rapid City, SD
  Capacity: 200 MW
  Commissioned: 2003

- Sidney, NE
  Capacity: 200 MW
  Commissioned: 1984

- Clovis, NM
  Capacity: 200 MW
  Commissioned: 1984

- Miles City, MT
  Capacity: 140 MW
  Commissioned: 1983

- Stegall, NE
  Capacity: 110 MW
  Commissioned: 1977

- Lamar, CO
  Capacity: 210 MW
  Commissioned: 2005

Transmission data provided by Ventyx, 2016 and was acquired from a wide variety of data sources including original research.
Identifying the Value of Cross Seam Transmission

Design 1

Design 2a

Design 2b

Design 3
Preliminary (Unpublished) Results

- Study evaluates trillions of dollars in investments
- Annual benefits are in the 10s of billions of dollars
- All transmission expansions pay for themselves in 15 years (2024-2038), over the life of the asset the value could be much larger
- Clearly there is a value to increased transmission connections between the east and west

RESULT PRELIMINARY - DO NOT CITE

<table>
<thead>
<tr>
<th>ECONOMICS, NPV $B</th>
<th>Design 1</th>
<th>Delta 2a</th>
<th>Delta 2b</th>
<th>Delta 3b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Investment Cost</td>
<td>61.21</td>
<td>12.68</td>
<td>13.67</td>
<td>18.89</td>
</tr>
<tr>
<td>Total non-Transmission Costs</td>
<td>2,211.49</td>
<td>-31.54</td>
<td>-45.17</td>
<td>-47.77</td>
</tr>
<tr>
<td>Benefit to Cost Ratio</td>
<td>2.49</td>
<td>3.3</td>
<td>2.53</td>
<td></td>
</tr>
</tbody>
</table>
### REFutures in the East: Base Scenario

<table>
<thead>
<tr>
<th>Region</th>
<th>Wind (%)</th>
<th>Solar PV (%)</th>
<th>Hydro (%)</th>
<th>Total wind + solar + hydro</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRCC</td>
<td>0%</td>
<td>35%</td>
<td>0%</td>
<td>35%</td>
</tr>
<tr>
<td>ISO-NE</td>
<td>46%</td>
<td>23%</td>
<td>6%</td>
<td>75%</td>
</tr>
<tr>
<td>MISO</td>
<td>80%</td>
<td>23%</td>
<td>2%</td>
<td>105%</td>
</tr>
<tr>
<td>NYISO</td>
<td>51%</td>
<td>23%</td>
<td>16%</td>
<td>90%</td>
</tr>
<tr>
<td>PJM</td>
<td>39%</td>
<td>28%</td>
<td>1%</td>
<td>67%</td>
</tr>
<tr>
<td>SERC</td>
<td>3%</td>
<td>29%</td>
<td>3%</td>
<td>36%</td>
</tr>
<tr>
<td>SPP</td>
<td>154%</td>
<td>21%</td>
<td>1%</td>
<td>176%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>47%</td>
<td>27%</td>
<td>2.6%</td>
<td>76%</td>
</tr>
</tbody>
</table>

- Nuclear plants retired
- No hurdle rates between regions in Base scenario
- ERGIS Sub-Regions define flow limits
- VG can provide reserves
- ERGIS reserve methodology
- Study on power flow and balancing; does not consider inertia or voltage stability
## Scenarios

<table>
<thead>
<tr>
<th>Base</th>
<th>High VG</th>
<th>Hurdle Rate</th>
<th>Inflexible Baseload</th>
<th>Local Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERGIS Thermal and Hydro Assumptions</td>
<td>Increase VG by 10% in all regions</td>
<td>Include $10/MWh charge on imports</td>
<td>~25% of all Baseload capacity in each region given ERGIS Nuclear flexibility</td>
<td>25% of all regional load must be served by local thermal or hydro resources</td>
</tr>
<tr>
<td>ERGIS ITx30 Transmission</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76% RE, 74% VG VG (pre-curtailment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear units retired</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseload units (all ERGIS coal units) have coal flexibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Increase VG by 10% in all regions
- Include $10/MWh charge on imports
- ~25% of all Baseload capacity in each region given ERGIS Nuclear flexibility
- Always committed at full load when not on an outage
- 25% of all regional load must be served by local thermal or hydro resources
U.S. EI curtailment ranges from 7-14%
Less flexible scenarios cost billions more to operate

Less flexible scenarios reduce on/off cycling costs, but not enough to reduce benefit from displaced fuel and O&M costs.

<table>
<thead>
<tr>
<th></th>
<th>% Difference from Base Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>High VG</td>
<td>-7%</td>
</tr>
<tr>
<td>Inflexible Baseload</td>
<td>4%</td>
</tr>
<tr>
<td>Local Conventional</td>
<td>7%</td>
</tr>
<tr>
<td>Hurdle Rate</td>
<td>4%</td>
</tr>
</tbody>
</table>
Conclusions

• Balancing 70-75% renewables (67% - 72% wind and solar) at 5-min levels in the Eastern Interconnection is possible.
• 99.99% of required reserves were procured in the annual grid simulation.
• Curtailment was simulated to range between 7.3% and 10.2% if grid operations are flexible.
• Flexibility challenges led to 9-14% curtailment, making achieving 70% renewables more challenging.
• More research is needed to understand dynamic stability and voltage issues, and whether additional constraints or technologies may be necessary to operate these scenarios reliably.
Outline

• Global Renewable Energy Markets Update
• Technology Overviews
  ➢ Wind and Solar
    ✦ Market Segments
    ✦ Global and US Markets
    ✦ Cost Trends
    ✦ Status in Colorado
• Power Systems Research – High Wind and Solar Penetrations
• Trends in Storage
Different technologies can address different grid needs, but no single storage technology, in the near term, is likely to meet all grid applications.
Tesla has 100 days to build a 129 MWh storage plant in South Australia

Dive Brief:

- South Australia Premier Jay Weatherill last week announced that Tesla has won a solicitation to build a 100 MW, 129 MWh energy storage project at a wind farm operated by Neoen of France.

- The storage facility will be "built and working" within 100 days of contract signature or it will be free, keeping with an offer made by Tesla CEO Elon Musk in March.

- The project will be located at Neoen’s 315 MW Hornsdale wind farm that is under construction. When completed, it would be the world's largest lithium-ion battery installation.
One year ago, GTM projected 217 $/kWhr in 2020

81% Reduction (!)
Public Service Company of Colorado

2016 Electric Resource Plan
2017 All Source Solicitation 30-Day Report
(Public Version)
(CPUC Proceeding No. 16A-0396E)

December 28, 2017
# Xcel RFP Responses

## RFP Responses by Technology

<table>
<thead>
<tr>
<th>Generation Technology</th>
<th># of Bids</th>
<th>Bid MW</th>
<th># of Projects</th>
<th>Project MW</th>
<th>Price or Equivalent</th>
<th>Pricing Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion Turbine/IC Engines</td>
<td>30</td>
<td>7,141</td>
<td>13</td>
<td>2,466</td>
<td>$4.80</td>
<td>$/kW-mo</td>
</tr>
<tr>
<td>Combustion Turbine with Battery Storage</td>
<td>7</td>
<td>804</td>
<td>3</td>
<td>476</td>
<td>6.20</td>
<td>$/kW-mo</td>
</tr>
<tr>
<td>Gas-Fired Combined Cycles</td>
<td>2</td>
<td>451</td>
<td>2</td>
<td>451</td>
<td></td>
<td>$/kW-mo</td>
</tr>
<tr>
<td>Stand-alone Battery Storage</td>
<td>28</td>
<td>2,143</td>
<td>21</td>
<td>1,614</td>
<td>11.30</td>
<td>$/kW-mo</td>
</tr>
<tr>
<td>Compressed Air Energy Storage</td>
<td>1</td>
<td>317</td>
<td>1</td>
<td>317</td>
<td></td>
<td>$/kW-mo</td>
</tr>
</tbody>
</table>

| Wind and Solar                              | 96        | 42,278 | 42            | 17,380     | $18.10              | $/MWh         |
| Wind with Battery Storage                   | 11        | 5,700  | 8             | 5,097      | 21.00               | $/MWh         |
| Solar (PV)                                  | 152       | 29,710 | 75            | 13,435     | 29.50               | $/MWh         |
| Wind and Solar and Battery Storage          | 7         | 4,048  | 7             | 4,048      | 30.60               | $/MWh         |
| Solar (PV) with Battery Storage             | 87        | 16,725 | 59            | 10,813     | 36.00               | $/MWh         |
| IC Engine with Solar                         | 1         | 5      | 1             | 5          |                     | $/MWh         |
| Waste Heat                                  | 2         | 21     | 1             | 11         |                     | $/MWh         |
| Biomass                                     | 1         | 9      | 1             | 9          |                     | $/MWh         |

**Total:** 430 Bids, 111,963 MW, 238 Projects, 58,283 MW
Thanks!
david.mooney@nrel.gov