indəˈspyʊədəb(ə)l: Five *indisputable* facts on modern power systems

Aaron Bloom, Hannele Holttinen, Udi Helman, Kate Summers, Jordan Bakke, Gregory Brinkman, and Anthony Lopez

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• **Fact one:** The grid can handle more renewable generation than previously thought.

• **Fact two:** Geographic and resource diversity provide additional reliability to the system.

• **Fact three:** Wind and solar forecasting provide significant value.

• **Fact four:** Our electric power markets were not originally designed for variable renewables—but they could be adapted.

• **Fact five:** Modern power electronics are creating new sources of essential reliability services.
FACT ONE: THE GRID CAN HANDLE MORE RENEWABLE GENERATION THAN PREVIOUSLY THOUGHT.
Fact One: The grid can handle more renewable generation than previously thought.

- Wind and solar didn’t become a big thing until recently.
- Issue 1 Power and Energy Magazine worked to define renewable energy.
- Installed capacity of non-hydro renewables in 2000 was very low.

<table>
<thead>
<tr>
<th>Region</th>
<th>Other/Renewable (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>18</td>
</tr>
<tr>
<td>Western Europe</td>
<td>10</td>
</tr>
<tr>
<td>Asia and Oceania</td>
<td>4</td>
</tr>
<tr>
<td>Rest of world</td>
<td>3</td>
</tr>
<tr>
<td>Global</td>
<td>35</td>
</tr>
</tbody>
</table>


Fact One: The grid can handle more renewable generation than previously thought.

<table>
<thead>
<tr>
<th>Region</th>
<th>Country</th>
<th>Instantaneous Penetration of Asynchronous Generation as a Percentage of Load</th>
<th>Annual Penetration of Asynchronous Generation as a Percentage of Load</th>
<th>Peak Load (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>Denmark</td>
<td>140% (2015)</td>
<td>42% (2015)</td>
<td>6,000 (2013)</td>
</tr>
<tr>
<td>EirGrid</td>
<td>Ireland</td>
<td>60% (2017)</td>
<td>22% (2016)</td>
<td>4,700 (2016)</td>
</tr>
<tr>
<td>ERCOT</td>
<td>United States</td>
<td>50% (2017)</td>
<td>15% (2016)</td>
<td>71,000 (2016)</td>
</tr>
<tr>
<td>MISO</td>
<td>United States</td>
<td>22% (2016)</td>
<td>8% (2016)</td>
<td>120,700 (2016)</td>
</tr>
<tr>
<td>South Australia Grid</td>
<td>Australia</td>
<td>119% (2016)</td>
<td>35% (2016)</td>
<td>2,895 (2016)</td>
</tr>
</tbody>
</table>
FACT TWO: GEOGRAPHIC AND RESOURCE DIVERSITY PROVIDE ADDITIONAL RELIABILITY TO THE SYSTEM.
Fact Two: Geographic and resource diversity provide additional reliability to the system.

• Joining together power systems to take advantage of diversity is not a new idea.

• But the value of and opportunity to access diversity has never been greater.

Chicago Tribune Power Plan 1927
Fact Two: Geographic and resource diversity provide additional reliability to the system.

- Temporal and Spatial diversity occur across time
- Optimized transmission network operation enables nearly all services to be shared:
  - Capacity,
  - Energy,
  - Ancillary Services.

Spatial variability of DNI in India
Fact Two: Geographic and resource diversity provide additional reliability to the system.

- MISO covers the most geographic territory of any single system.
- MISO North has experienced very high regional penetrations, 80% instantaneous.
- Leverages large network to balance needs across space and time.
FACT THREE: WIND AND SOLAR FORECASTING PROVIDE SIGNIFICANT VALUE.
Fact Three: Wind and solar forecasting provide significant value.

- Wind and solar are not totally unpredictable
- Aggregate forecast errors impact commitment and dispatch
- Day ahead forecasts are more valuable
- Real time forecasts are more accurate

Forecast error for aggregated wind power production due to spatial smoothing.
Fact Three: Wind and solar forecasting provide significant value.

- Two approaches to solar forecasting
  - Irradiance forecasts
  - Statistical models
- Significant improvements are being developed in ramp forecasts

Distribution of forecast errors at different geographic locations
FACT FOUR: OUR ELECTRIC POWER MARKETS WERE NOT ORIGINALLY DESIGNED FOR VARIABLE RENEWABLES—BUT THEY COULD BE ADAPTED.
Fact Four: Our electric power markets were not originally designed for variable renewables—but they could be adapted.

• Competitive Markets were designed to:
  – Incentivize efficient investment
  – Manage market power
  – Eliminate rate pancaking
  – Improve Unit Commitment
  – Price congestion
Fact Four: Our electric power markets were not originally designed for variable renewables—but they could be adapted.

CAISO’s Southern California Edison load aggregation point prices, hourly averages, January–April 2017
FACT FIVE: MODERN POWER ELECTRONICS ARE CREATING NEW SOURCES OF ESSENTIAL RELIABILITY SERVICES.
Fact Five: Modern power electronics are creating new sources of essential reliability services.

- Reliability falls into two categories
  - Adequacy: ability to supply aggregate demand
  - Operating Reliability: ability to withstand disturbances

- Essential Reliability Services
  - Load and Resource Balancing
  - Voltage Support
  - Frequency Support
Fact Five: Modern power electronics are creating new sources of essential reliability services.

- Both wind and solar can provide a range of reliability services
- New market and reliability rules are needed to ensure resources can offer full capabilities to market

WHERE DO THESE FACTS LEAD US?
Cleaner Energy Futures

WECC (high_solar) + ERGIS (RTx30)
05-12 03:00 EST

https://www.youtube.com/playlist?list=PLmIn8Hncs7bEI4P8z6-KCliwbYrwANv4p
WHAT DO WE NEED TO GET HERE?
WHAT DO WE NEED TO GO EVEN FARTHER?
Comprehensive reliability modeling

**Stability**
- Metrics:
  - Frequency Response
  - Inertia
  - Voltage
  - Impact of reserves
  - Area Control Error

**Operations**
- Metrics:
  - Production Costs
  - Unserved Energy
  - Market performance
  - Curtailment
  - Transmission congestion

**Resource Adequacy**
- Metrics:
  - Capital costs
  - Retirements and additions
  - Loss of Load Probability
  - Planning Reserve Margin *

Legend:
- Blue: Scenarios
- Orange: Data

Transmission scale:
- Nation
- State
- Metro

Time scales:
- Seconds
- Minutes
- Hours
- Years
- Decades
Enabling Comprehensive Modeling

• Papers
  – We need to clearly define Resource Adequacy, Balancing, and Stability
  – P. Kundur et al. (2003) is an excellent example of the path we need to follow
    • http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1318675&isnumber=29221

• Models
  – RTS-GMLC: https://github.com/GridMod/RTS-GMLC

• Data
  – Generation data is pretty good nationally: wind, solar, gas, coal, hydro
  – Load data is terrible
    • No good nodal load datasets
India Greening the Grid

Identifying cost-effective options for **strengthened interconnections** between the eastern and western grids of the U.S. electricity system.

Analyzing pathways to a **modernized power system** for North America through efficient infrastructure planning and system operations.

Exploring a more **electrified U.S. economy** and its implications for the energy system, electricity supply and demand, and infrastructure needs.

**SEAMS**
Interconnections Seam Study

**NARIS**
North American Renewable Integration Study

**EFS**
Electrification Futures Study

http://www.nrel.gov/analysis/seams.html
http://www.nrel.gov/analysis/naris.html
http://www.nrel.gov/analysis/electrification_futures.html