indəˈspyo͞o̅dəb(ə)l:

Five *indisputable* facts on modern power systems

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

IEEE PES General Meeting

July 16-20, 2017

Chicago, Illinois

NREL/PR-6A20-68947

indəˈspyo͞o̅dəb(ə)l

- **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.

H. B. Puttgen, et al , "Distributed generation: Semantic hype or the dawn of a new era?," in *IEEE Power and Energy Magazine*, vol. 1, no. 1, pp. 22-29, Jan-Feb 2003

S. Rahman, "Green power: what is it and where can we find it?," in *IEEE Power and Energy Magazine*, vol. 1, no. 1, pp. 30-37, Jan/Feb 2003

Region	Other/Renewable (GW)
North America	18
Western Europe	10
Asia and Oceania	4
Rest of world	3
Global	35

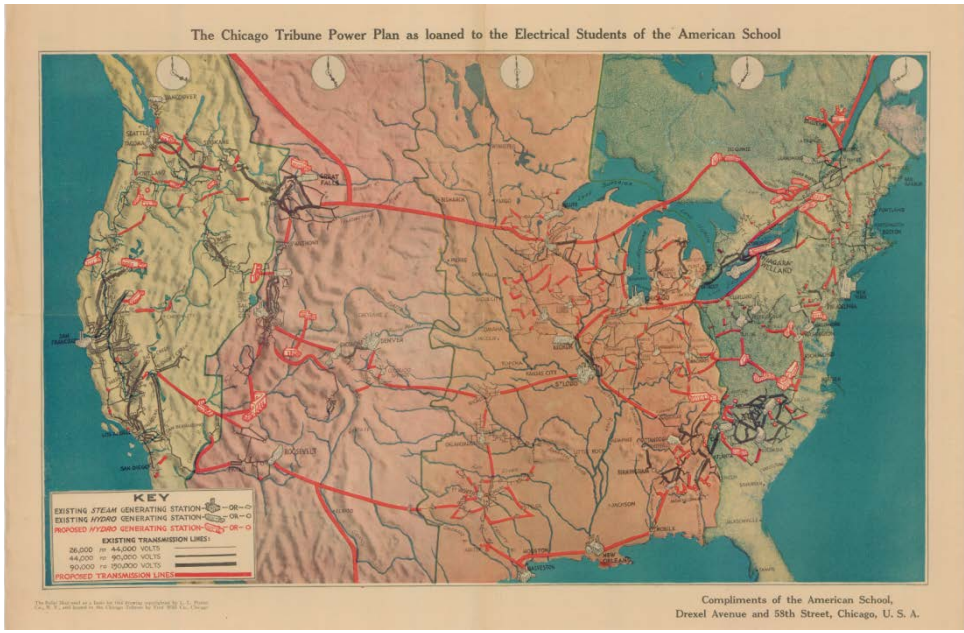
Fact One: The grid can handle more renewable generation than previously thought.

Region	Country	Instantaneous Penetration of Asynchronous Generation as a Percentage of Load	Annual Penetration of Asynchronous Generation as a Percentage of Load	Peak Load (MW)
CAISO	United States	49% (2017)	27% (2016)	46,232 (2016)
Denmark	Denmark	140% (2015)	42% (2015)	6,000 (2013)
EirGrid	Ireland	60% (2017)	22% (2016)	4,700 (2016)
ERCOT	United States	50% (2017)	15% (2016)	71,000 (2016)
MISO	United States	22% (2016)	8% (2016)	120,700 (2016)
Portugal	Portugal	104% (2015)	23% (2015)	8,300 (2015)
South Australia Grid	Australia	119% (2016)	35% (2016)	2,895 (2016)
Southwest Power Pool	United States	52% (2017)	14% (2015)	50,083 (2016)

FACT TWO: GEOGRAPHIC AND RESOURCE DIVERSITY PROVIDE ADDITIONAL RELIABILITY TO THE SYSTEM.

Fact Two: Geographic and resource diversity provide additional reliability to the system.

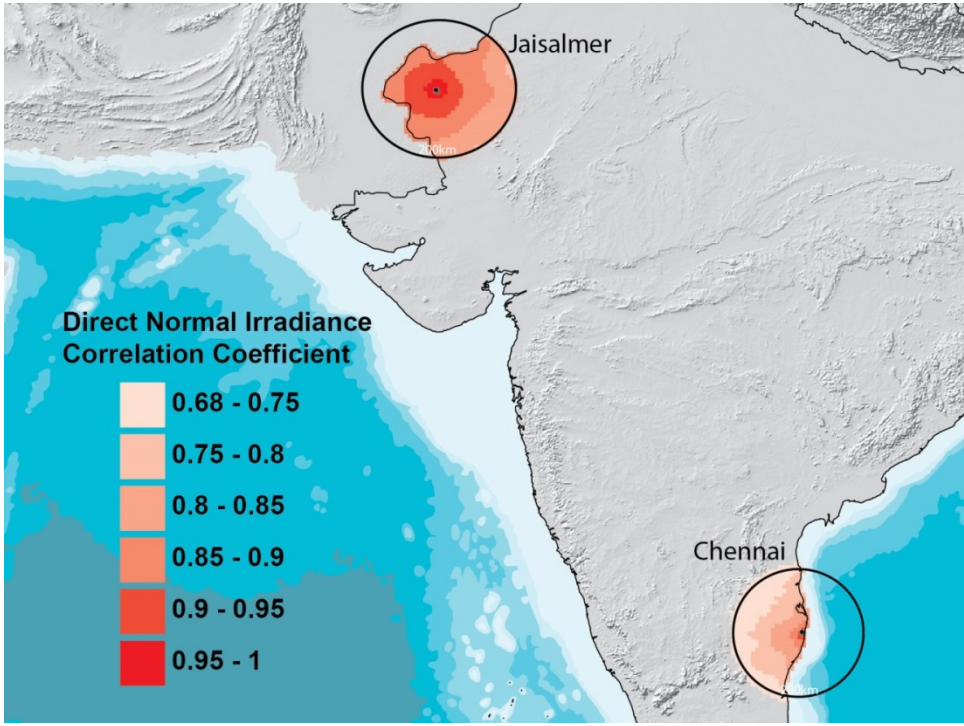
- Joining together power systems to take advantage of diversity is not a new idea.
- But the of value of and opportunity to access diversity has never been greater



Chicago Tribune Power Plan 1927

Fact Two: Geographic and resource diversity provide additional reliability to the system.

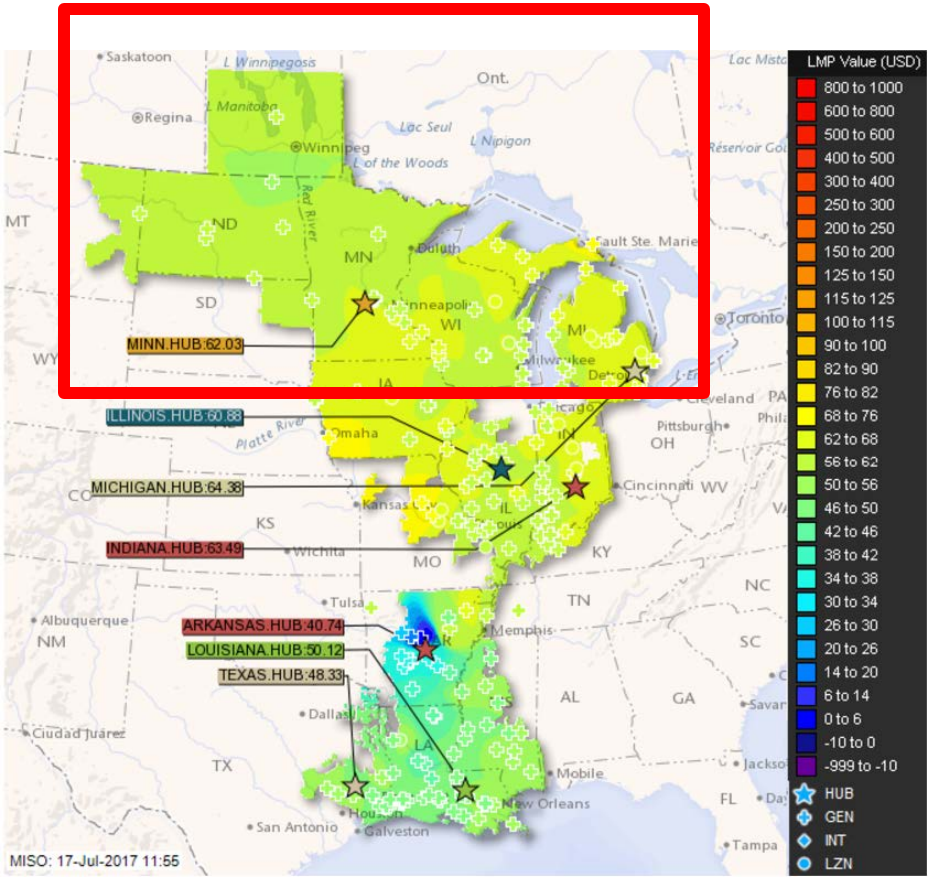
- Temporal and Spatial diversity occur across time
- Optimized transmission network operation enables nearly all services to be shared:
  - Capacity,
  - Energy,
  - Ancillary Services.



Spatial variability of DNI in India

Fact Two: Geographic and resource diversity provide additional reliability to the system.

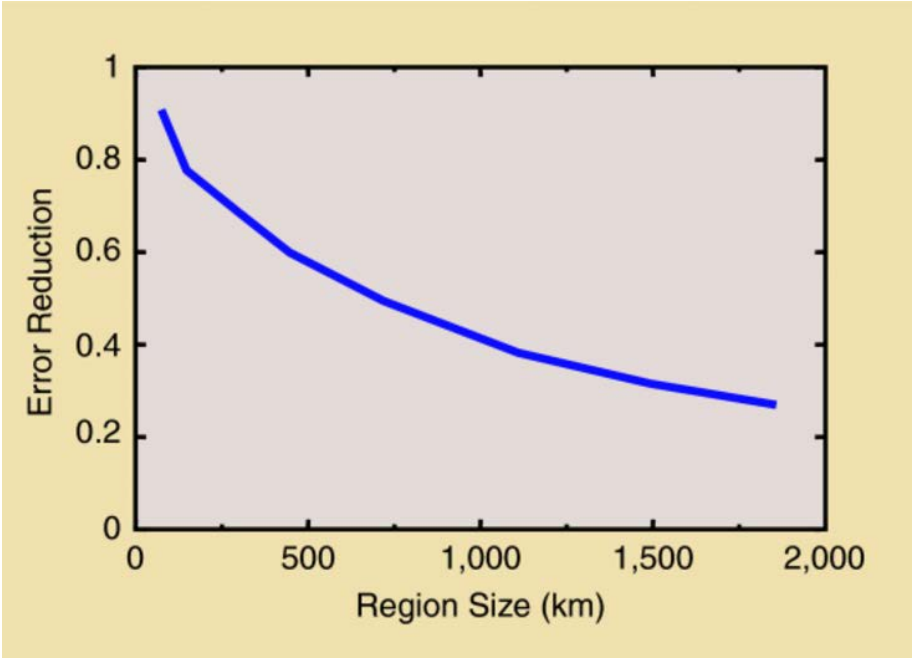
- MISO covers the most geographic territory of any single system
- MISO North has experienced very high regional penetrations, 80% instantaneous.
- Leverages large network to balance needs across space and time



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

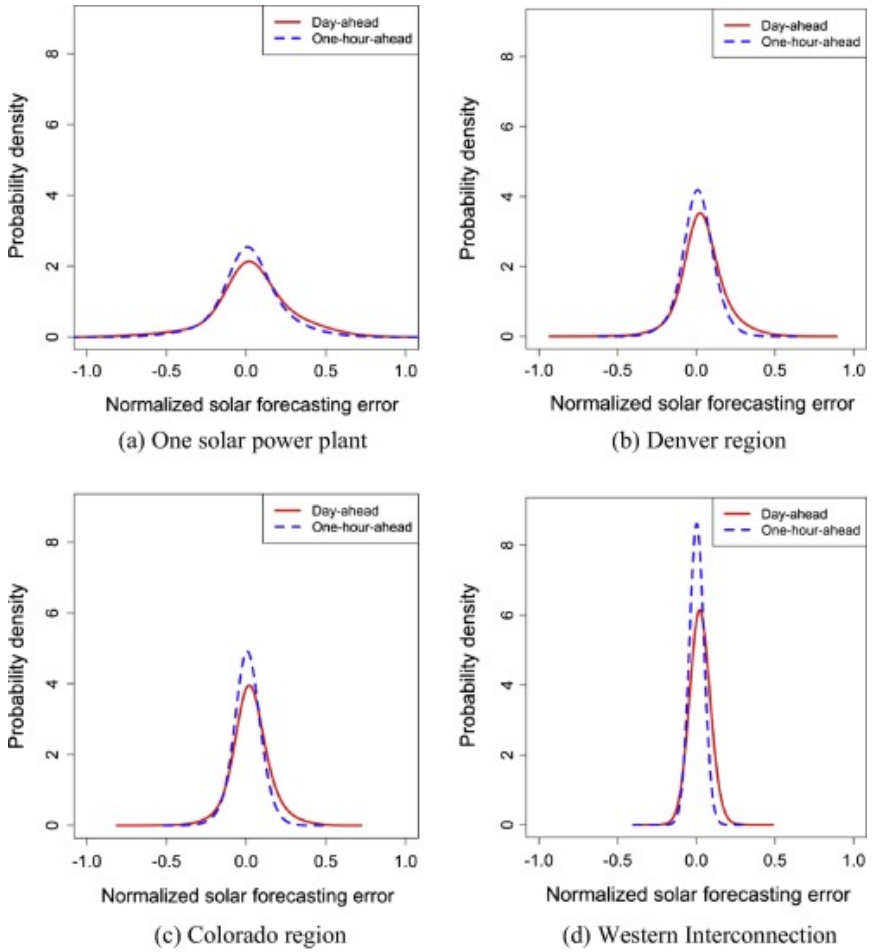


Forecast error for aggregated wind power production due to spatial smoothing.

Milligan et al Wind Power Myths Debunked (2003)
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5233741&isnumber=5233728

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



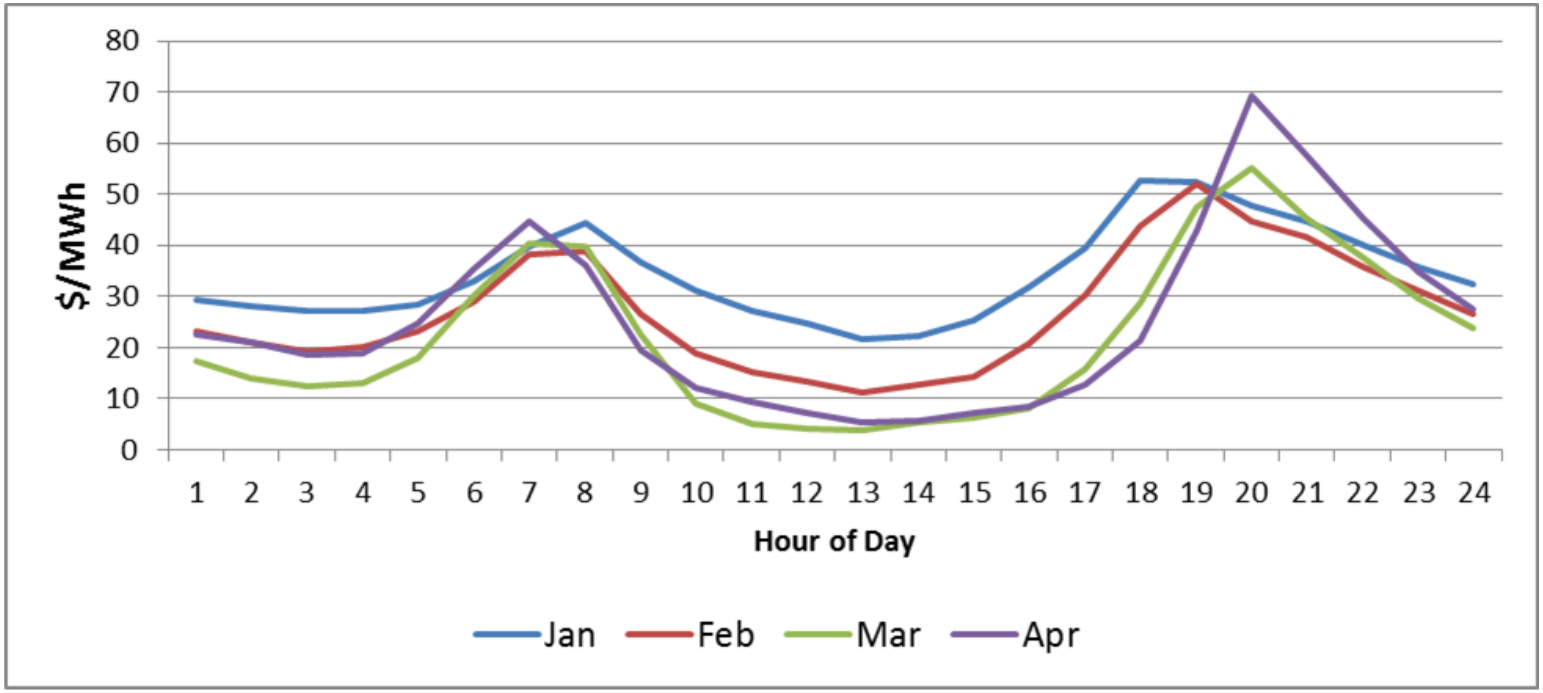
Distribution of forecast errors at different geographic locations
Zhang et al. (2013) http://www.nrel.gov/docs/fy14osti/60142.pdf

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

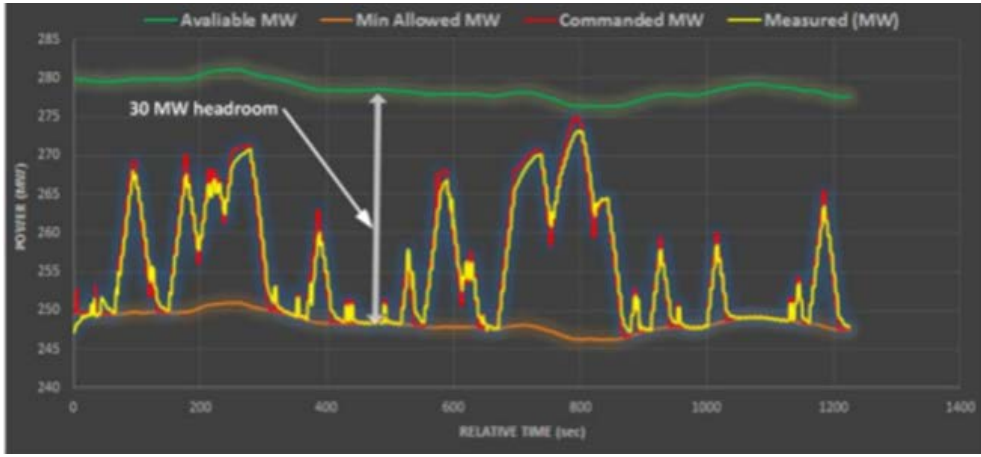
FACT FIVE: MODERN POWER ELECTRONICS ARE CREATING NEW SOURCES OF ESSENTIAL RELIABILITY SERVICES.

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



Loutan et al. (2017) http://www.nrel.gov/docs/fy17osti/67799.pdf

Table 2. Measured Regulation Accuracy by 300-MW PV Plant

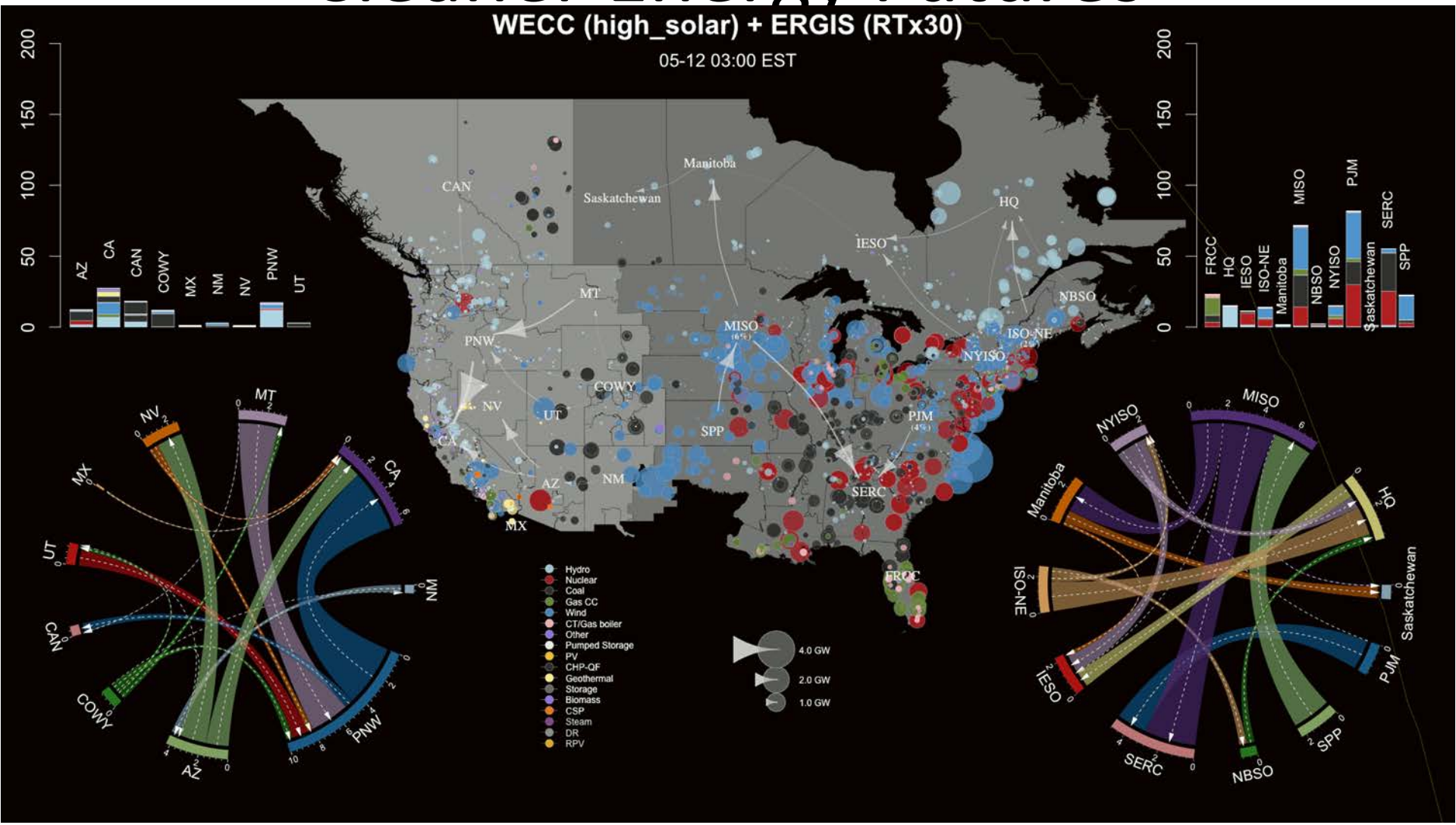
Time Frame	Measured Accuracy of Solar PV Plant
Sunrise	93.7%
Middle of the day	87.1%
Sunset	87.4%

Table 3. Typical Regulation-Up Accuracy of CAISO Conventional Generation

	Combined Cycle	Gas Turbine	Hydro	Limited Energy Battery Resource	Pump Storage Turbine	Steam Turbine
Regulation-Up Accuracy	46.88%	63.08%	46.67%	61.35%	45.31%	40%

WHERE DO THESE FACTS LEAD US?

Cleaner Energy Futures

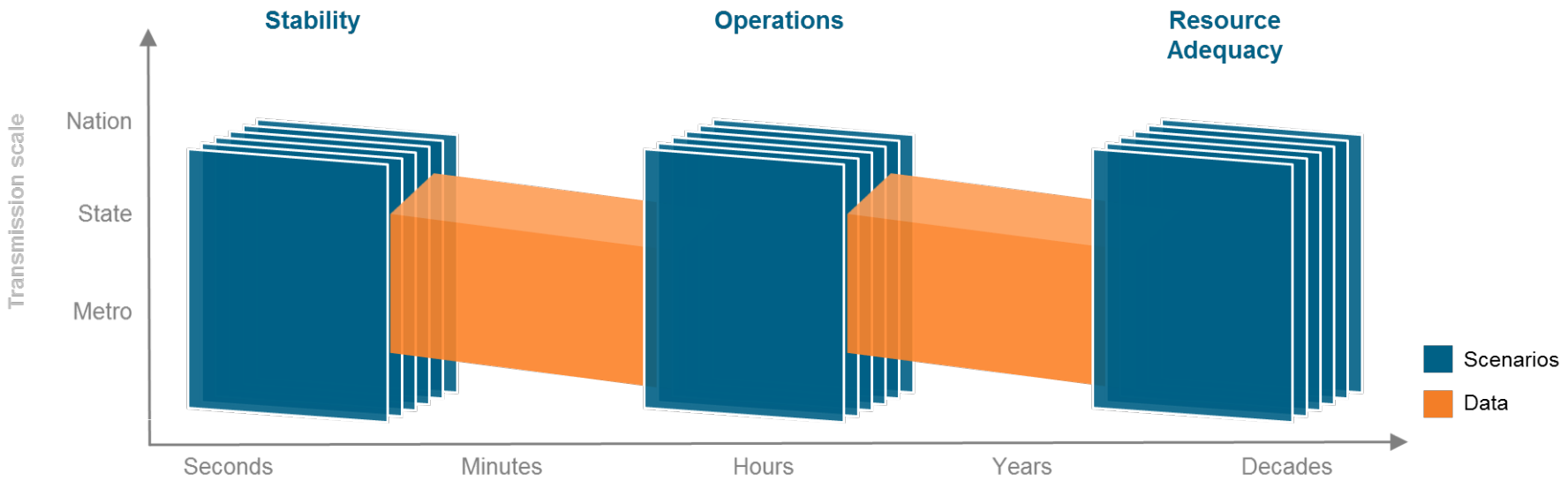


https://www.youtube.com/playlist?list=PLmIn8Hncs7bEl4P8z6-KCliwbYrwANv4p

WHAT DO WE NEED TO GET HERE?

WHAT DO WE NEED TO GO EVEN FARTHER?

Comprehensive reliability modeling



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

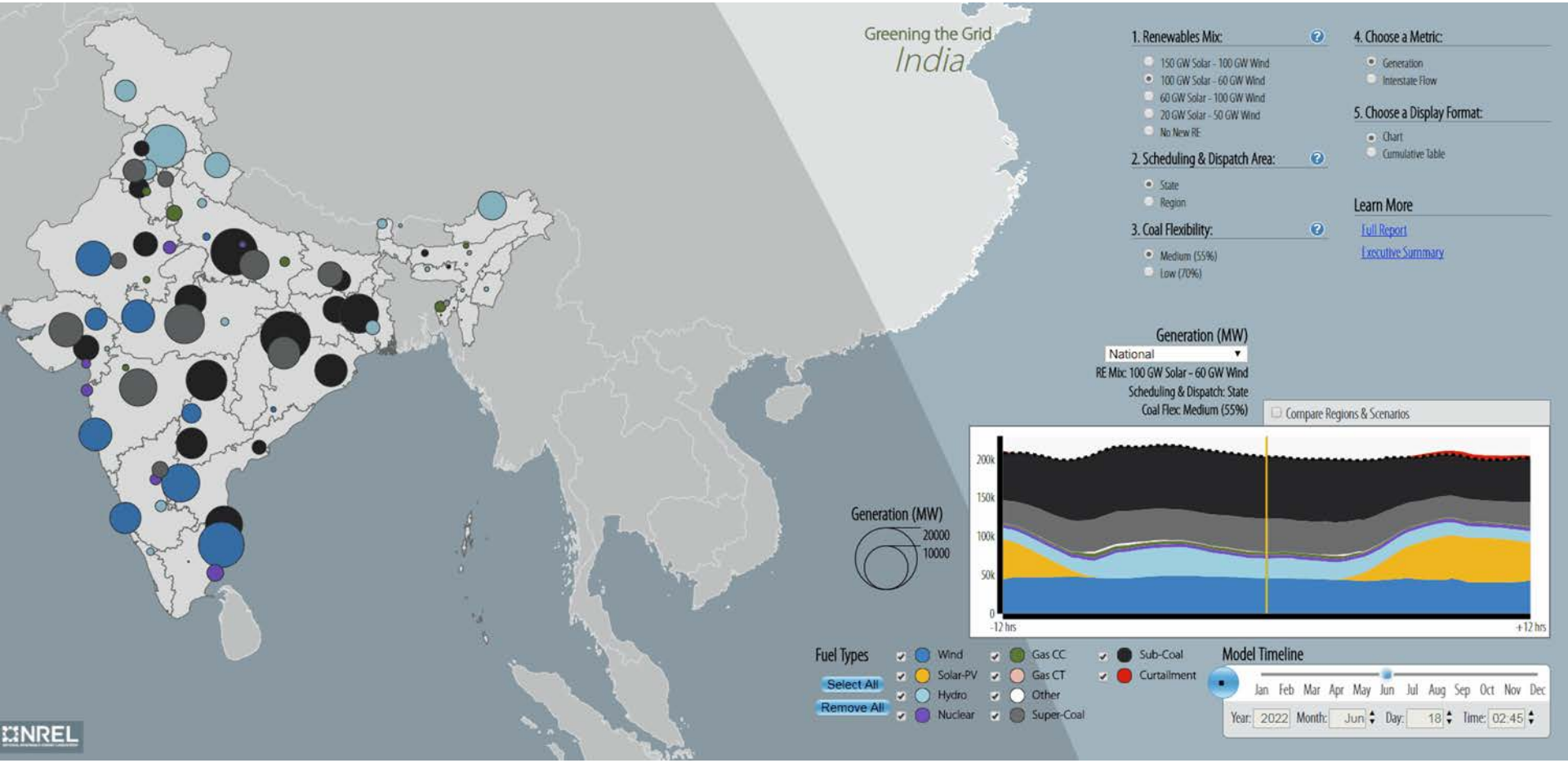
Metrics:
- Production Costs
- Unserved Energy
- Market performance
- Curtailment
- Transmission congestion

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

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

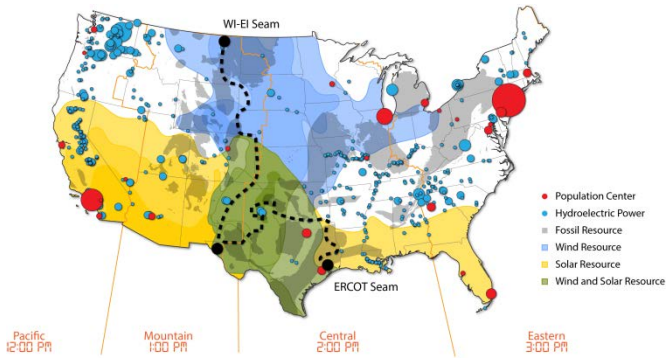
India Greening the Grid



http://www.nrel.gov/analysis/india-renewable-integration-study.html

SEAMS

Interconnections Seam Study



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

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

NARIS

North American Renewable Integration Study

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

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

EFS

Electrification Futures Study

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

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