NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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

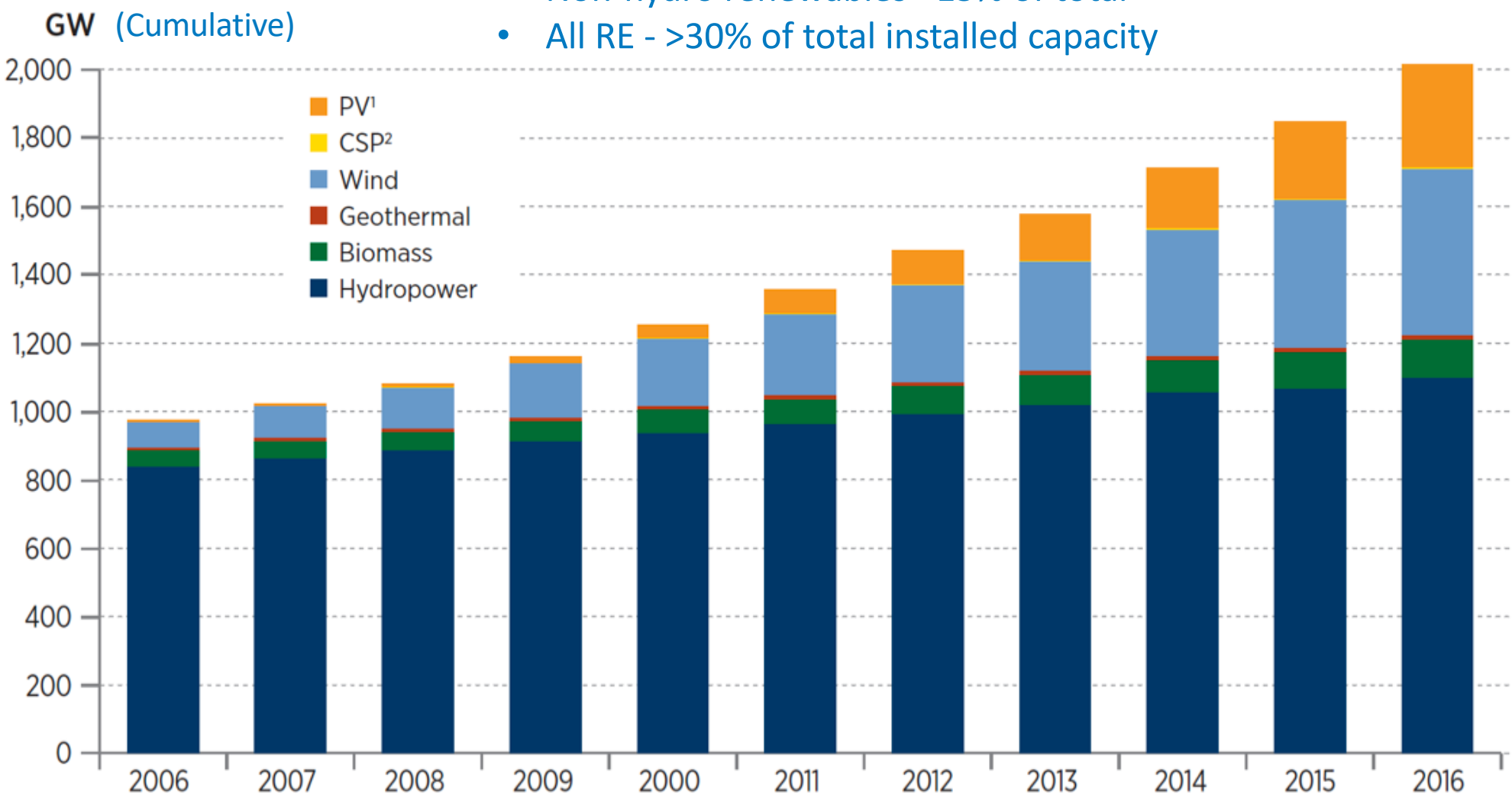
- Global Renewable Energy Markets Update
- Technology Overviews
  - Wind and Solar
    - Market Segments
    - Global and US Markets
    - Cost Trends
    - Status in Colorado
- Power Systems Research – High Wind and Solar Penetrations
- Trends in Storage

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

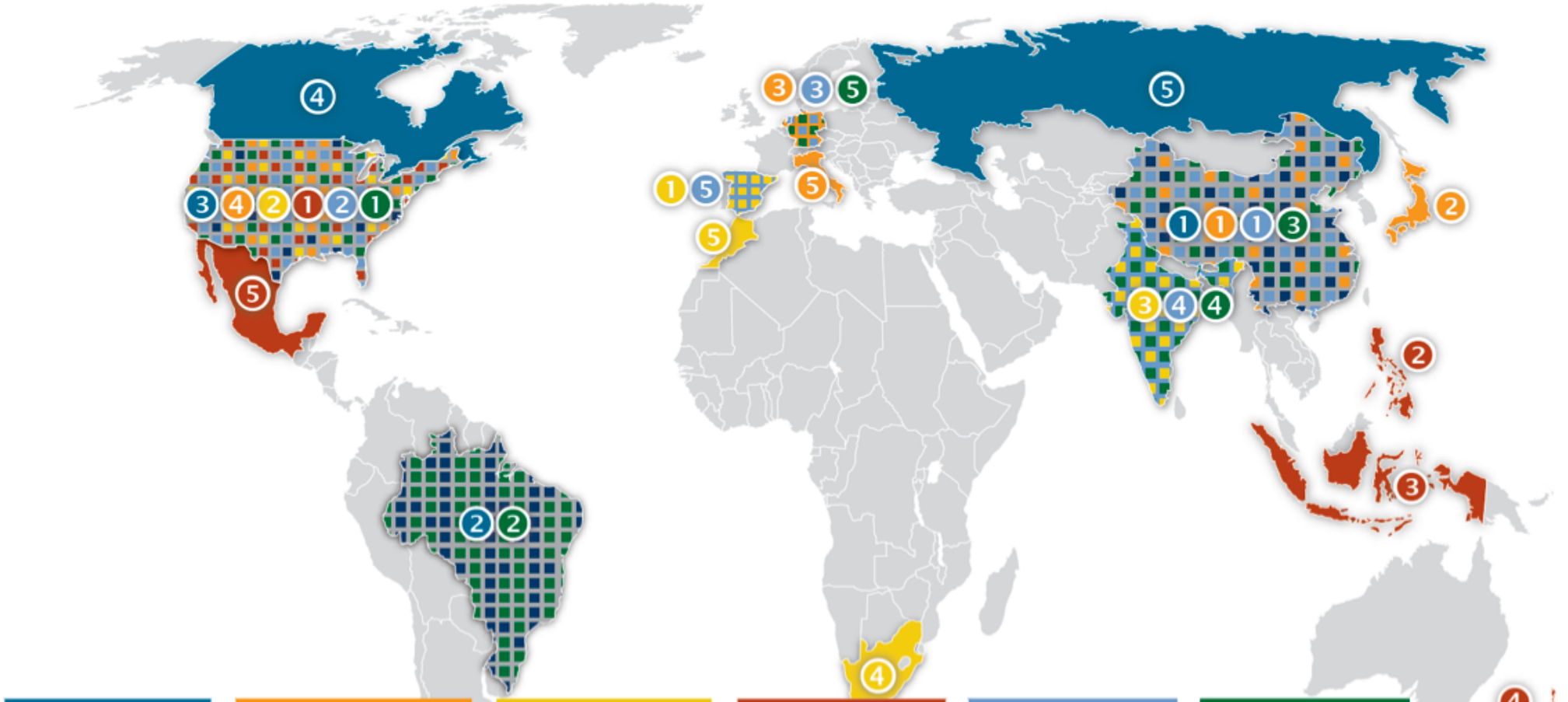
Global Renewable Energy Capacity

- 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



Hydropower	PV[1]	CSP	Geothermal	Wind	Biomass
1 China	1 China	1 Spain	1 United States	1 China	1 United States
2 Brazil	2 Japan	2 United States	2 Philippines	2 United States	2 Brazil
3 United States	3 Germany	3 India	3 Indonesia	3 Germany	3 China
4 Canada	4 United States	4 South Africa	4 New Zealand	4 India	4 India
5 Russia	5 Italy	5 Morocco	5 Mexico	5 Spain	5 Germany

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)

Wind Energy - Offshore

Westermeerwind Wind Farm

- Noordoostpolder, Netherlands
- 144 MW

Horn Rev Wind Farm

- West coast of Denmark
- 160 MW

Wind Energy - Onshore

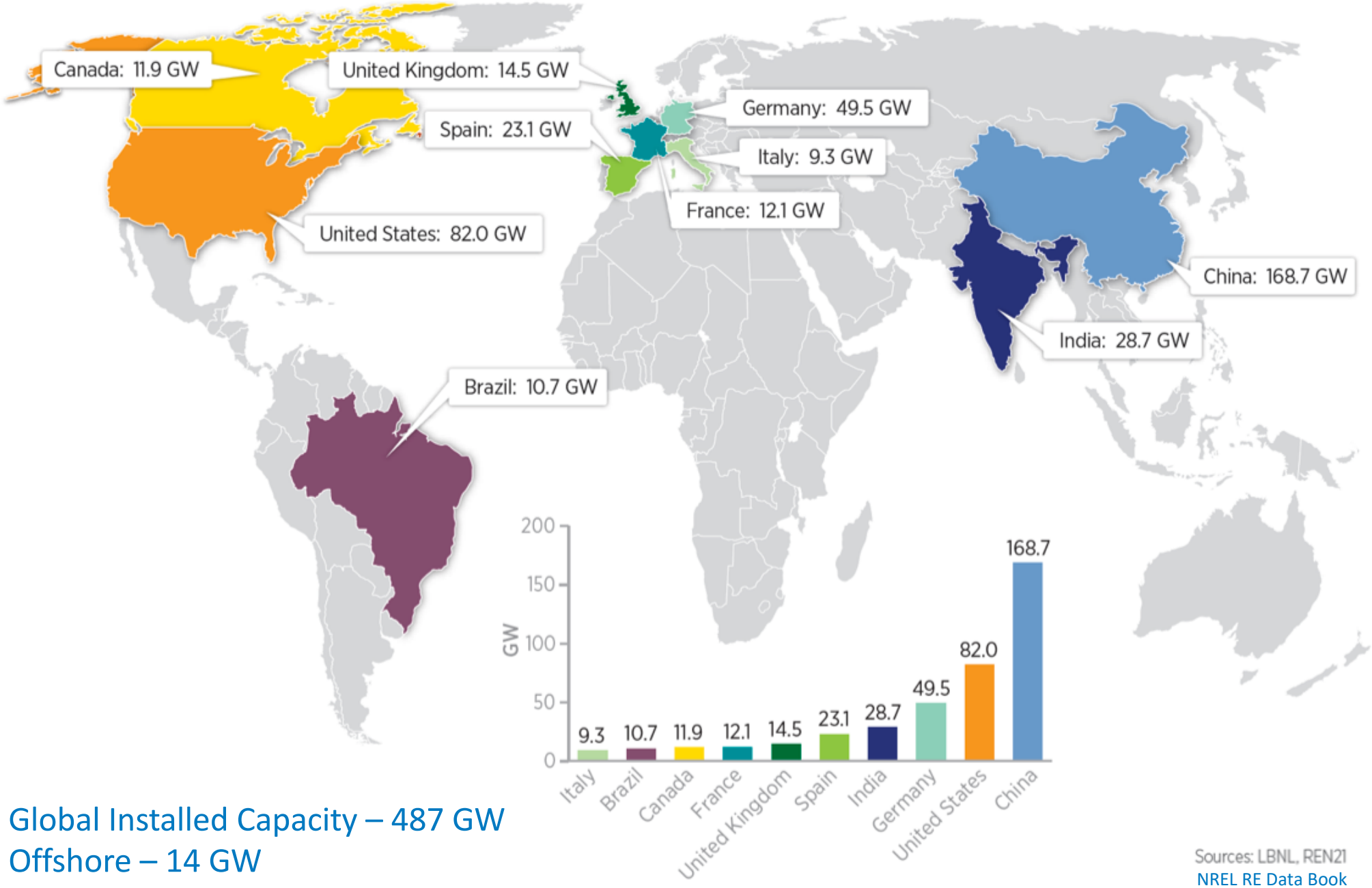
Peetz Table Wind Energy Center

- Peetz, Colorado
- 575 MW

Cedar Creek Wind Farm

- Grover, Colorado
- 550 MW

Global Wind Markets - 2016

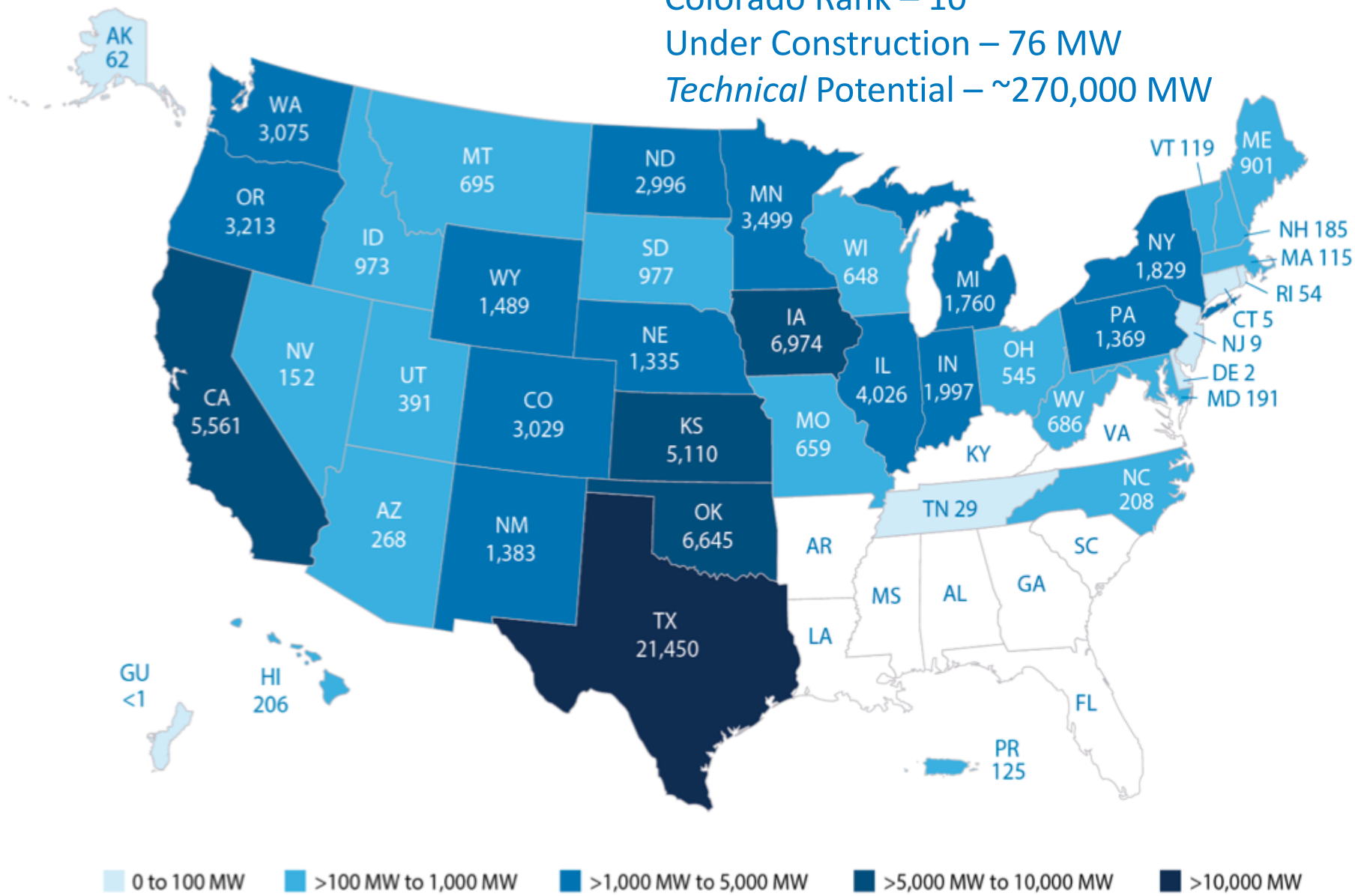


Global Installed Capacity – 487 GW
Offshore – 14 GW

Sources: LBNL, REN21
NREL RE Data Book

U.S. Wind Market

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



American Wind Energy Association | U.S. Wind Industry Third Quarter 2017 Market Report | AWEA Public Version

Colorado Wind Development

STATE WIND FACTS

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

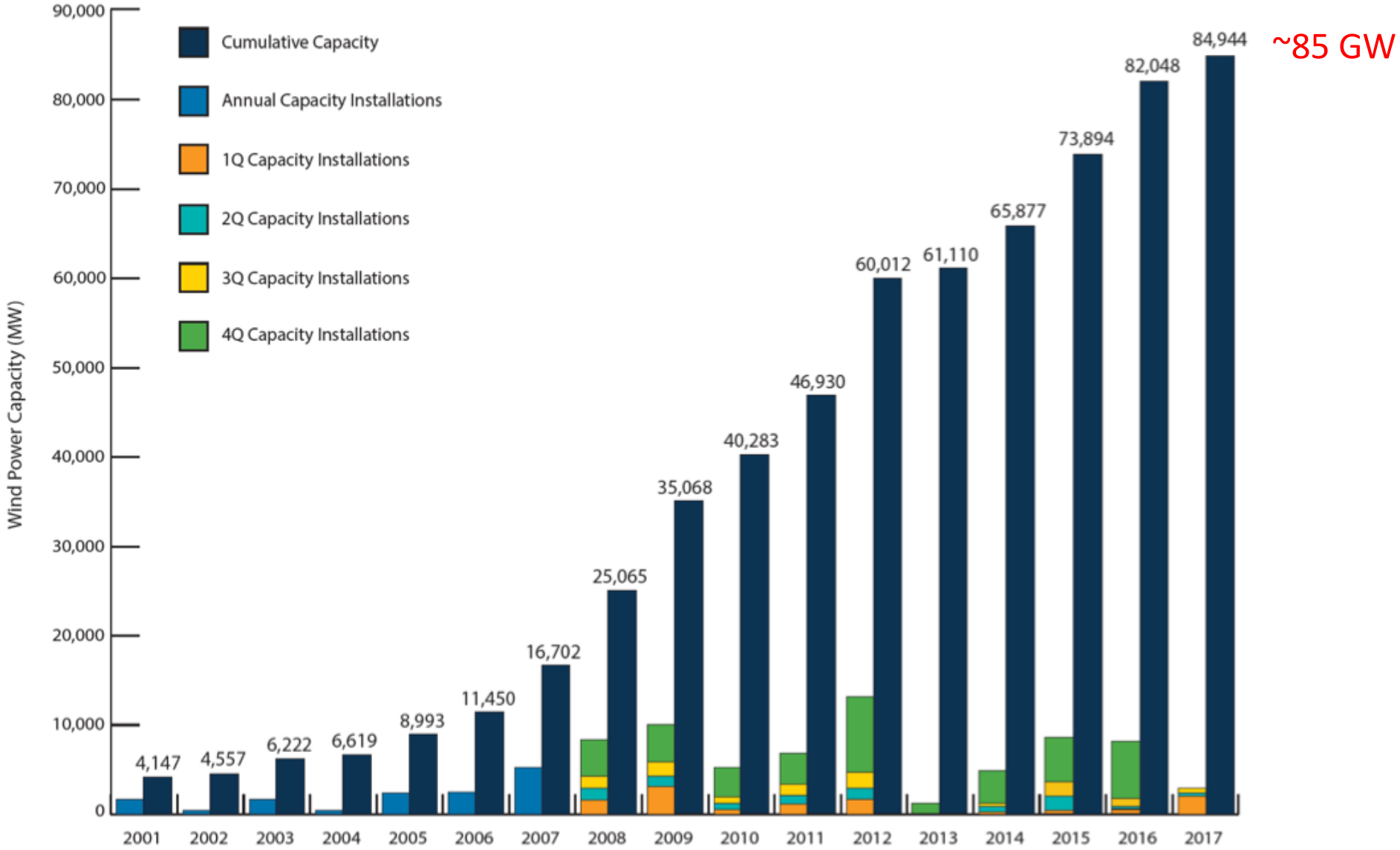
Generating wind power creates no emissions and uses virtually no water.

- **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 (CO_2) 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)

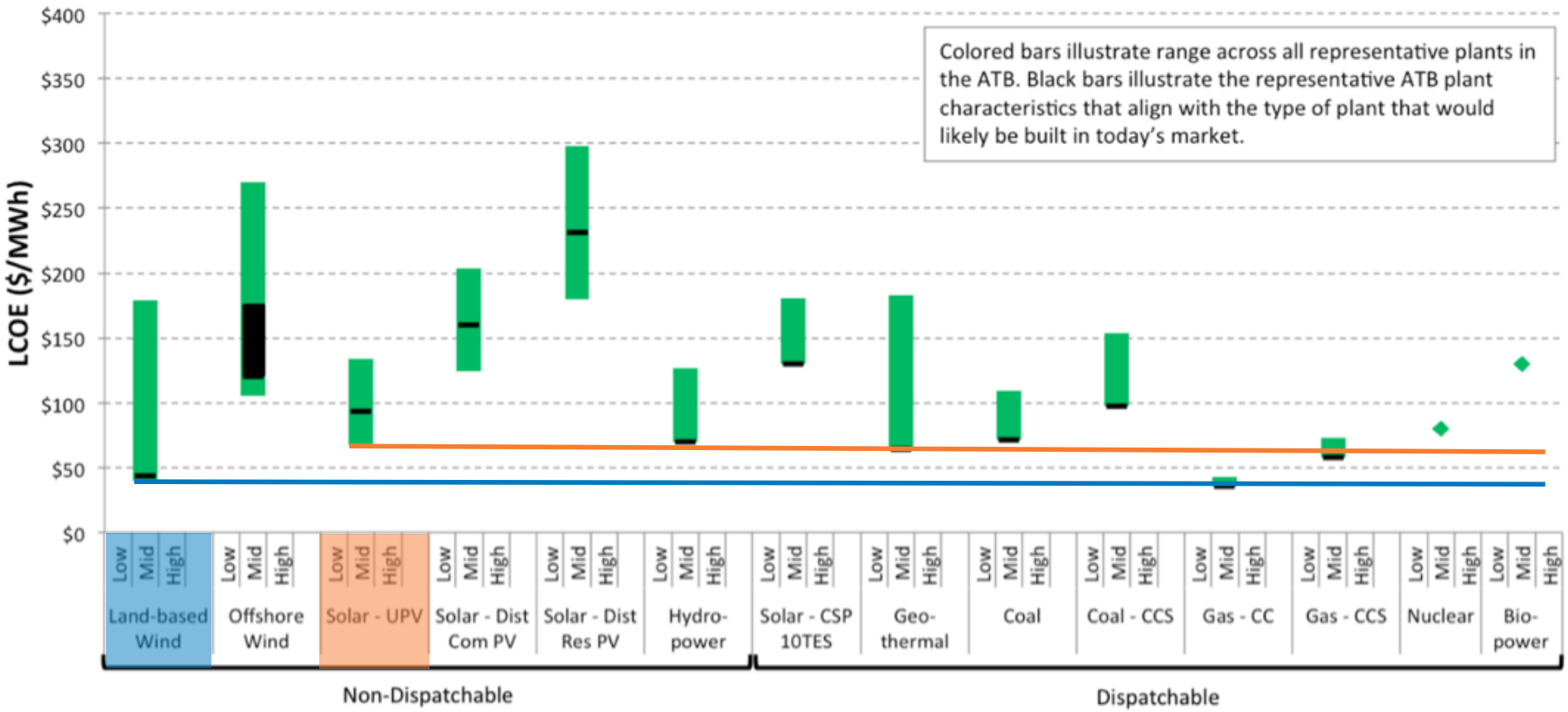


Note: Utility-scale wind capacity includes installations of wind turbines larger than 100-kW for the purpose of the AWEA U.S. Wind Industry Quarterly Market Reports. Annual capacity additions and cumulative capacity may not always add up due to decommissioned and repowered wind capacity. Wind capacity data for each year is continuously updated as information changes.

American Wind Energy Association | U.S. Wind Industry Third Quarter 2017 Market Report | AWEA Public Version

Cost Comparisons: NREL's Annual Technology Baseline

2017



Land-based Wind

Utility PV

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

Solar Energy

Golmud Solar Park, Western China – 200 MW

PV Markets – Residential

PV Markets – Commercial

Credit: IKEA

PV Markets – Utility

PV Markets – Utility

Desert Sunlight Solar Farm

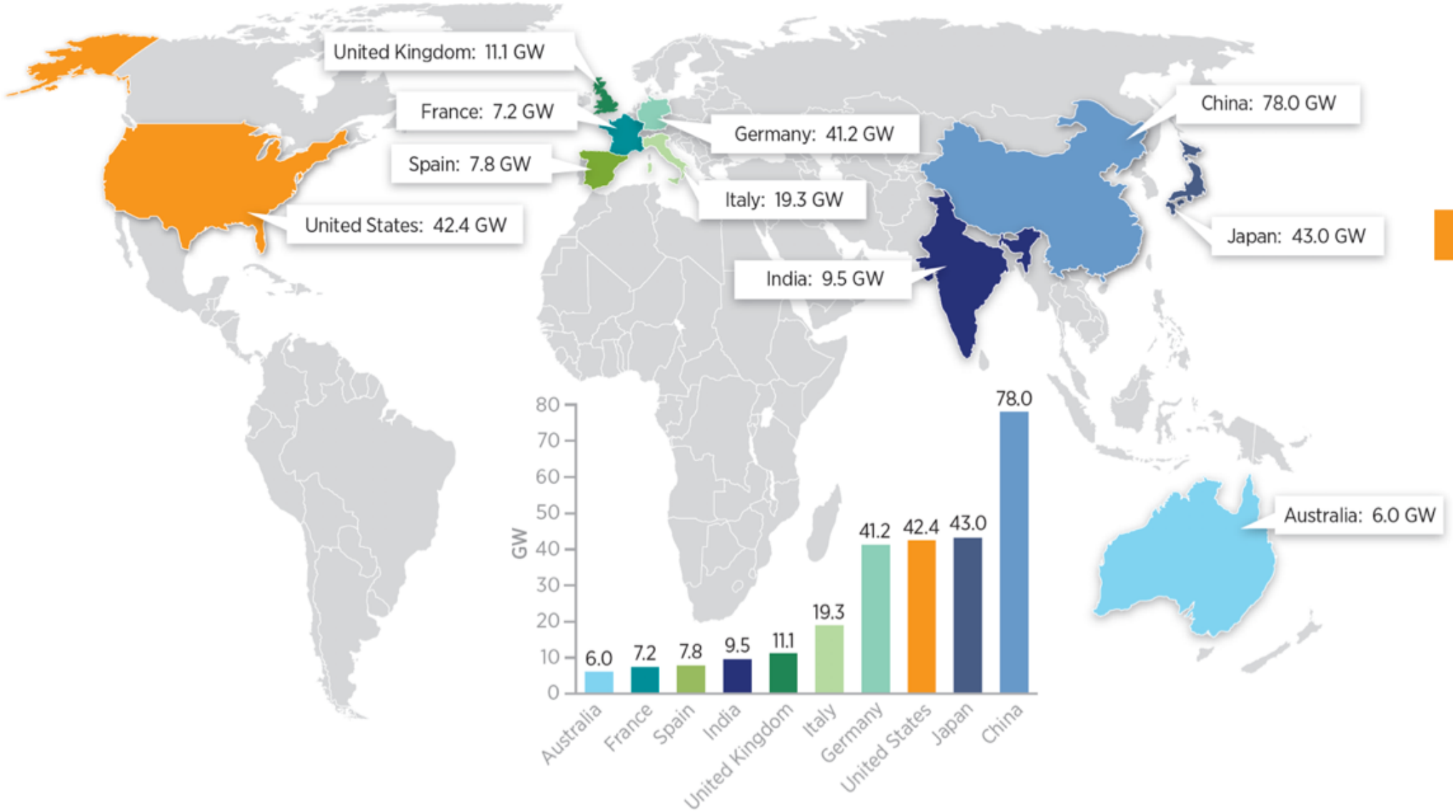
- NextEra Energy
- 8.8 million First Solar CdTe panels
- 550 Mwac
- 300,000 tons CO2 displaced
- 6.2 square miles
- End-to-end – 6,600 miles

PV Markets – Utility

Solar Star

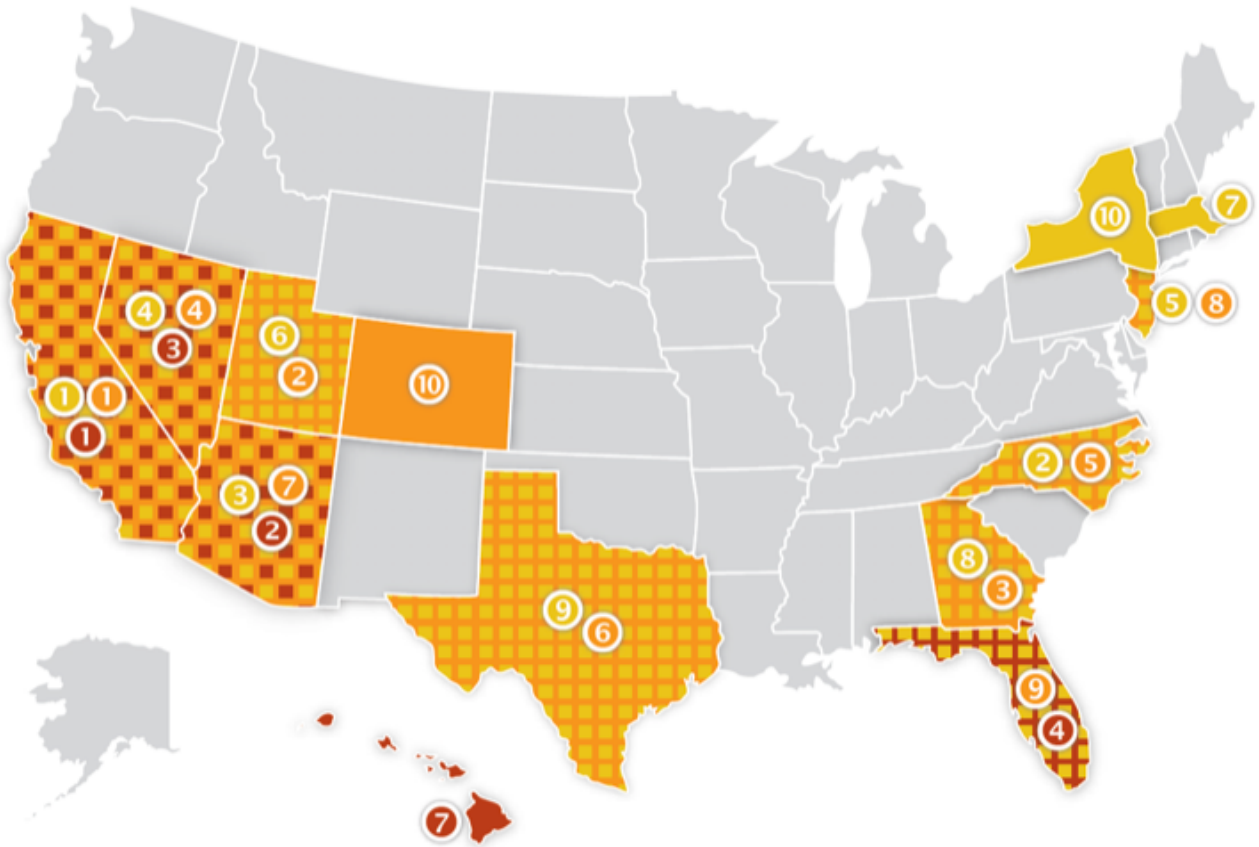
- BHE Renewables
- 1.7 million SunPower c-Si panels
- 579 Mwac
- 300,000 tons CO2 displaced
- 5 square miles
- End-to-end – 1,650 miles

Global Solar Energy Markets - 2016



Sources: REN21, SEIA/GTM
Includes CSP and grid-connected PV; capacity is reported in MWac.

U.S. Solar Deployment (2016)



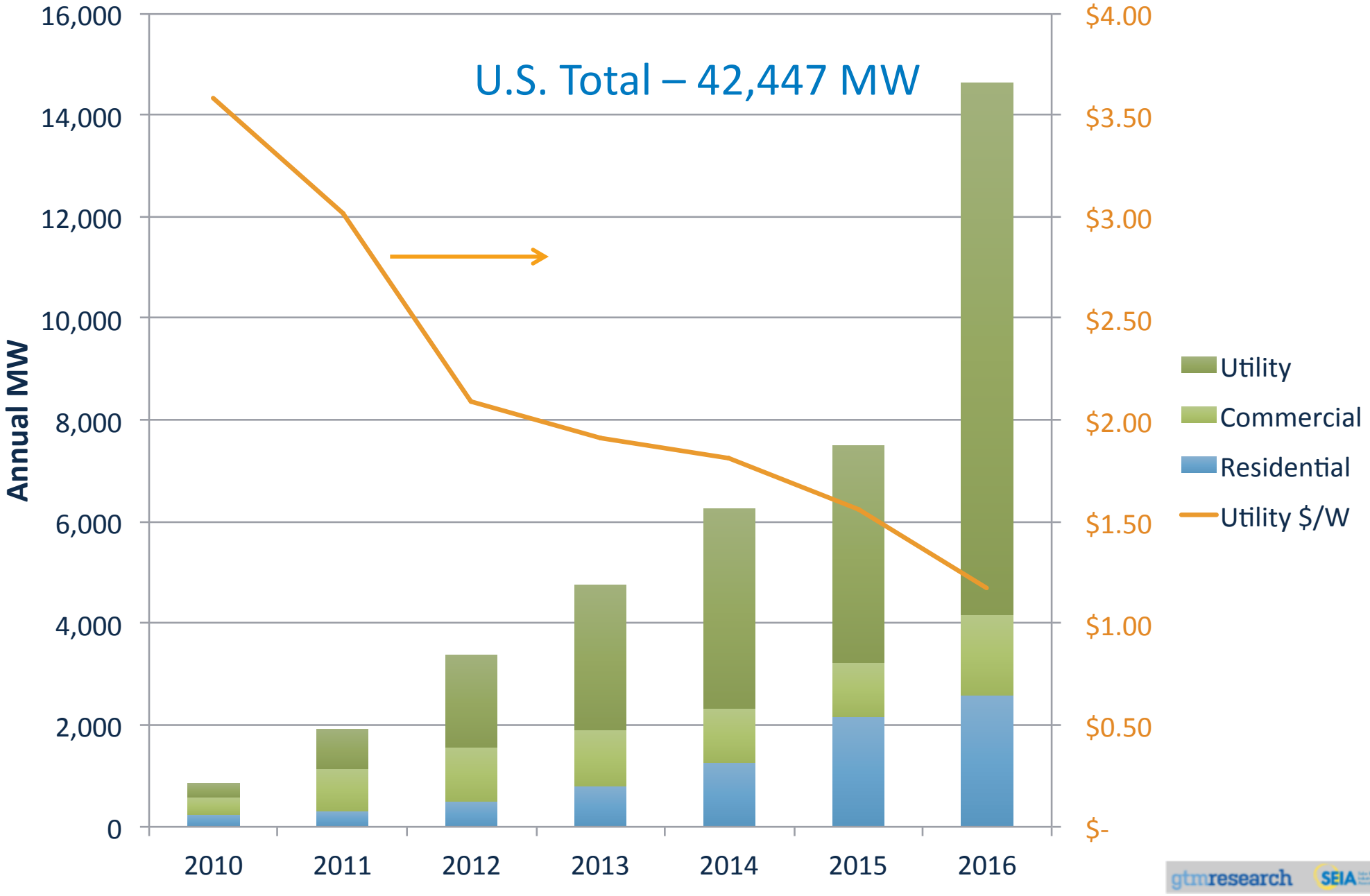
PV Cumulative Capacity[1] (MW)	
1 California	17,084
2 North Carolina	3,016
3 Arizona	2,700
4 Nevada	2,017
5 New Jersey	1,991
6 Utah	1,489
7 Massachusetts	1,487
8 Georgia	1,432
9 Texas	1,215
10 New York	927

PV Annual Capacity[1] Additions (MW)	
1 California	5,096
2 Utah	1,241
3 Georgia	1,023
4 Nevada	984
5 North Carolina	923
6 Texas	672
7 Arizona	657
8 Massachusetts	406
9 Florida	404
10 Colorado	382

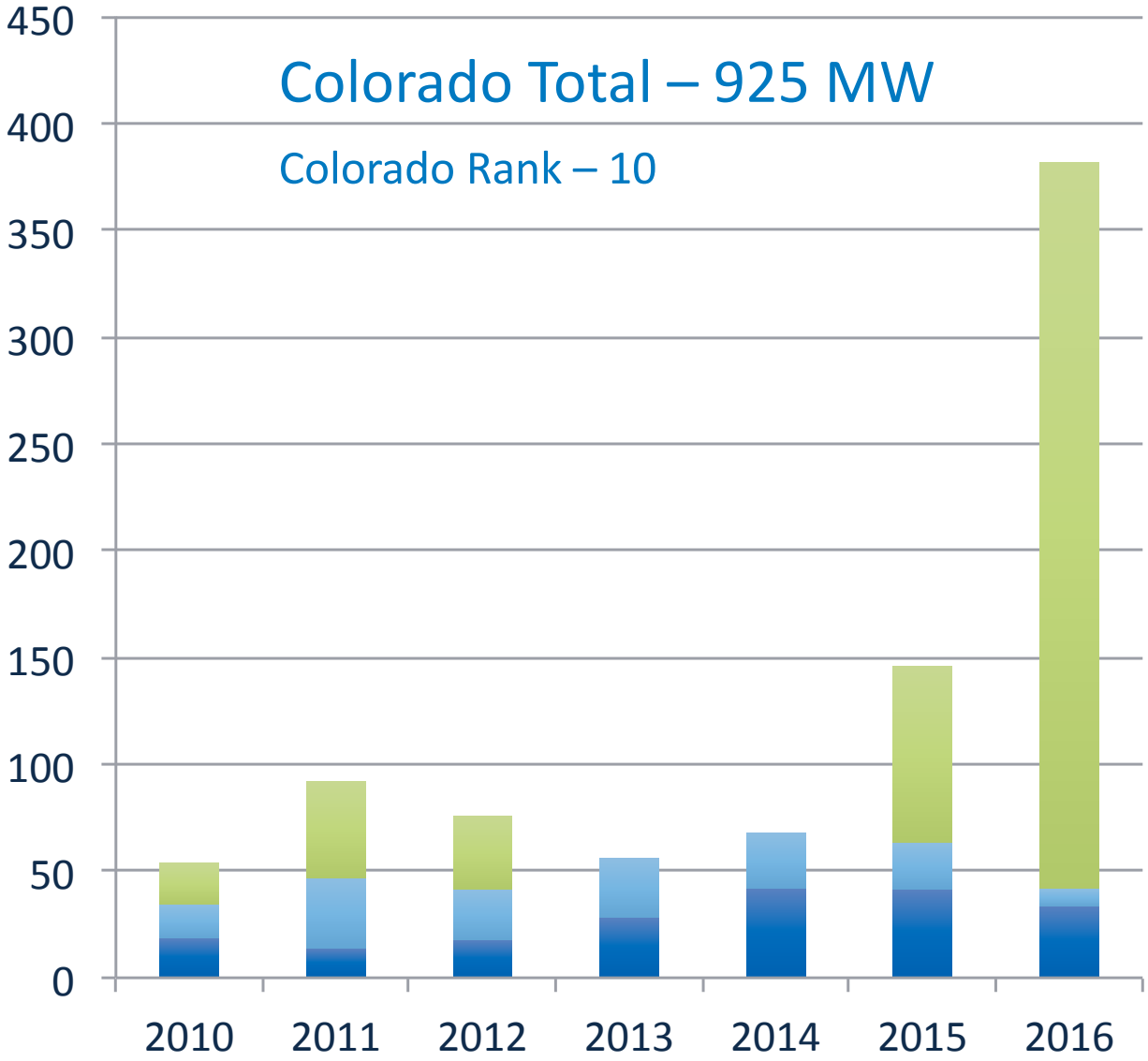
CSP Cumulative Capacity[2] (MW)	
1 California	1,256
2 Arizona	283
3 Nevada	174
4 Florida	75
7 Hawaii	7

Sources: NREL RE Databook, GTM/SEIA and IREC

Trends in PV Power



Colorado PV Market



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

Utility
Commercial
Residential

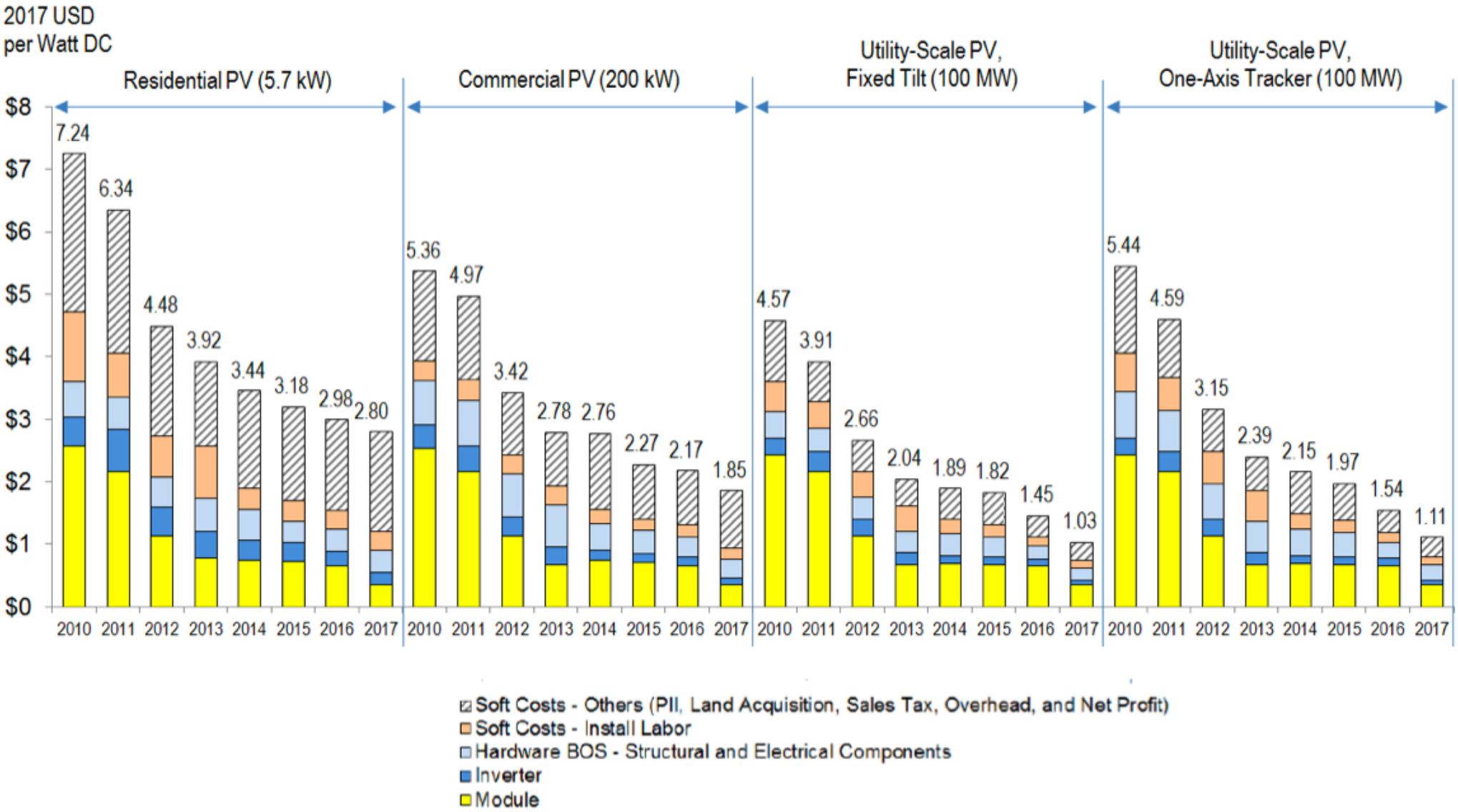
gtmresearch SEIA

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**.

Source: SEIA

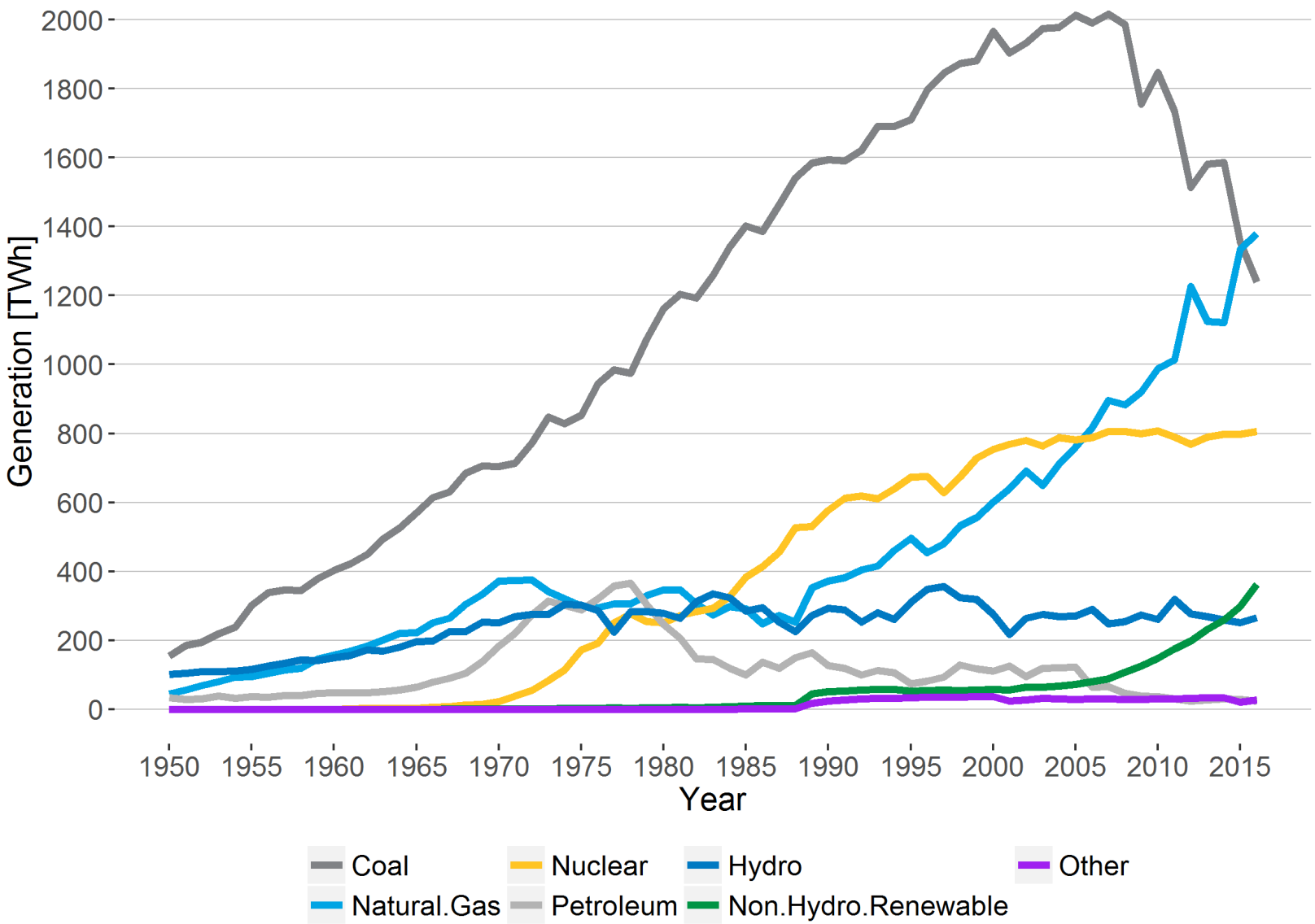
PV System Prices



Outline

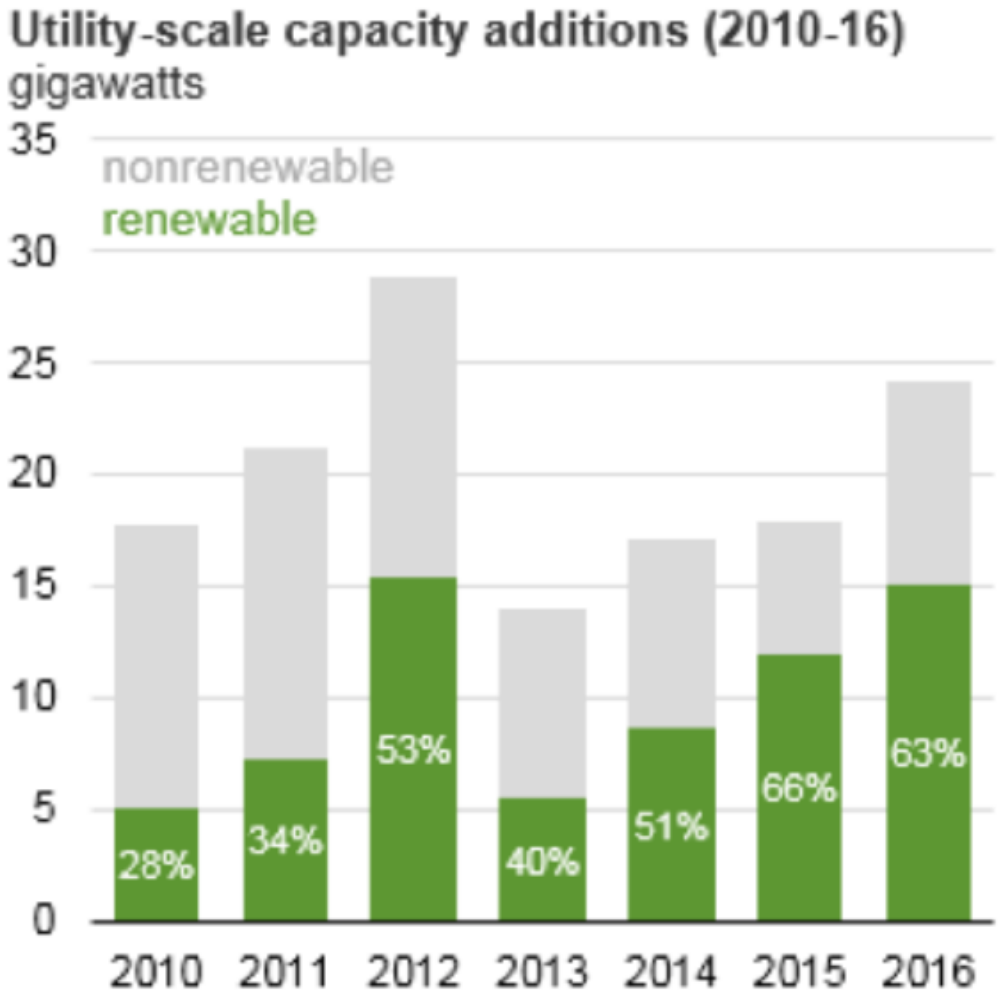
- Global Renewable Energy Markets Update
- Technology Overviews
  - Wind and Solar
    - Market Segments
    - Global and US Markets
    - Cost Trends
    - Status in Colorado
- Power Systems Research – High Wind and Solar Penetrations
- Trends in Storage

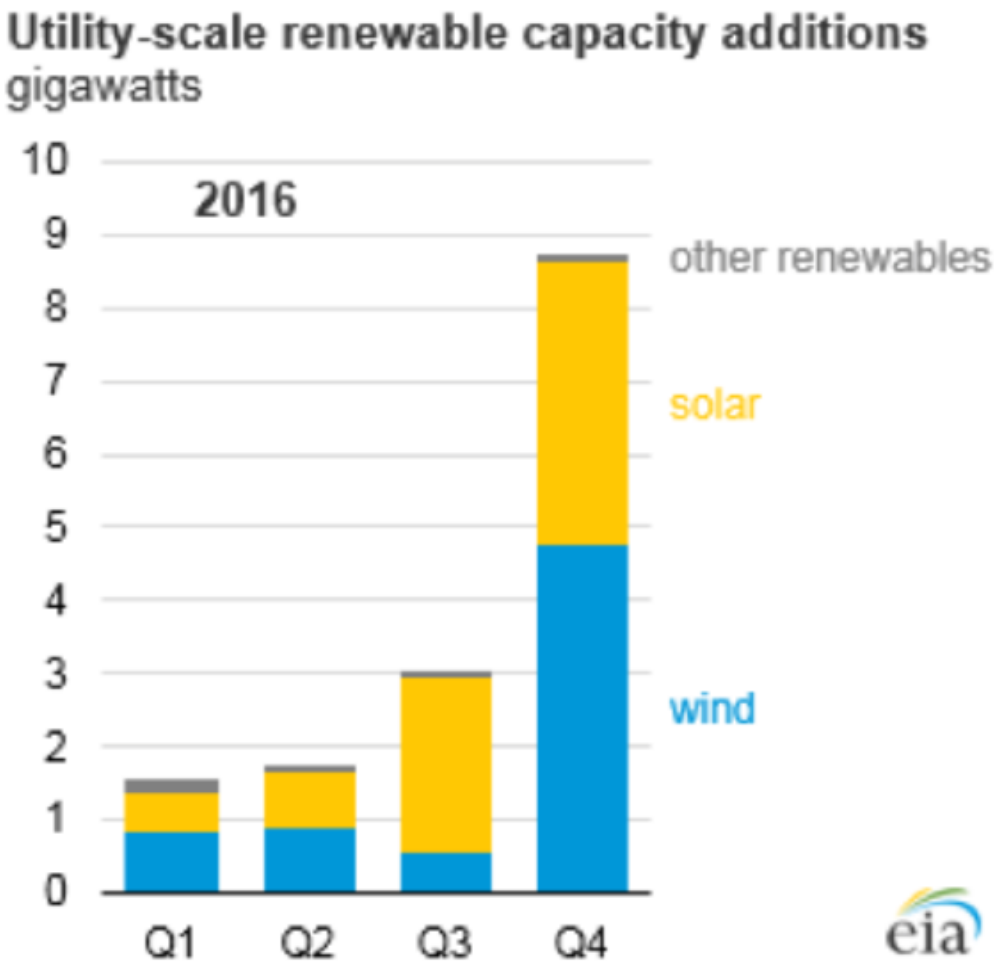
Trends in the U.S. Power System



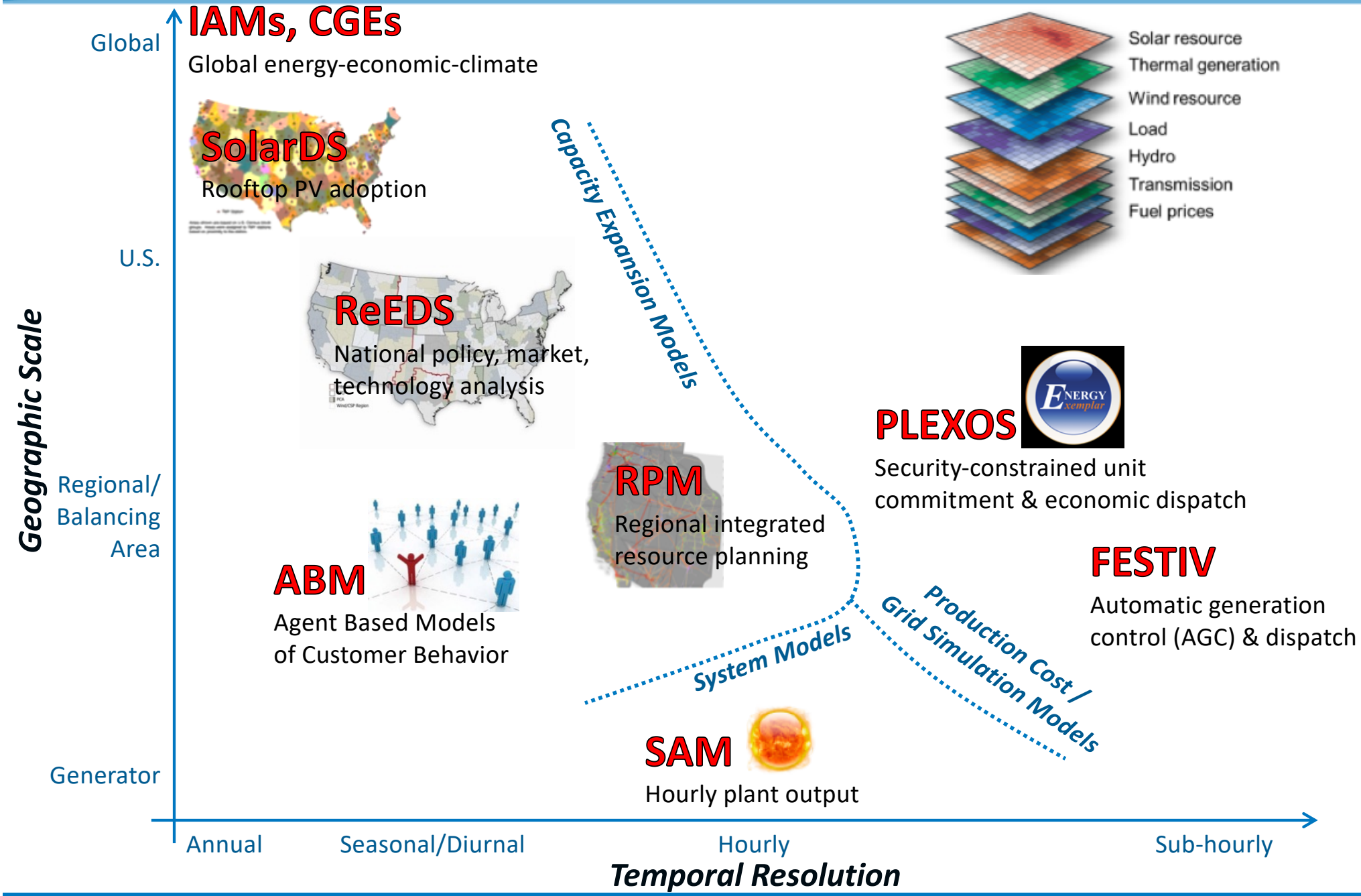
Source: EIA – Electric Power Annual

Trends in the U.S. Power System



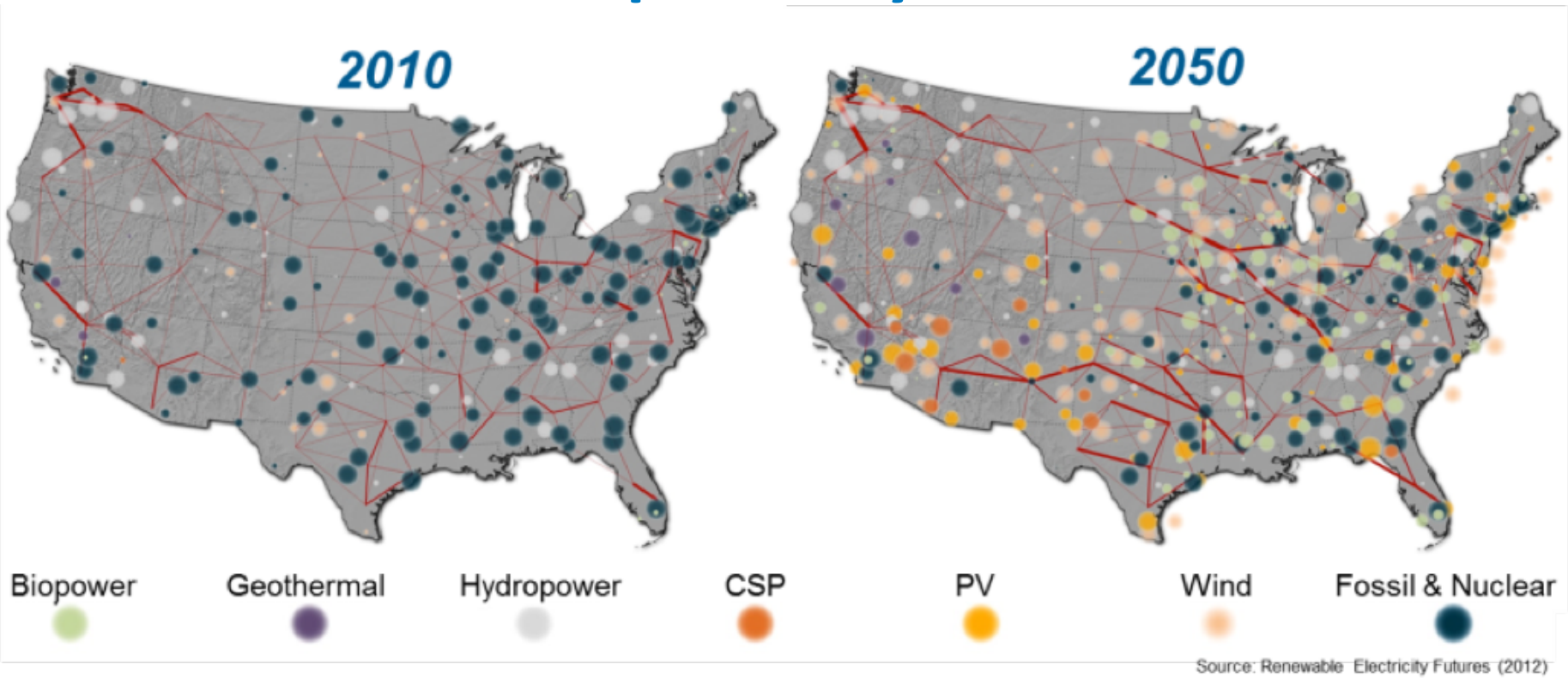


SEAC Electricity Modeling at Multiple Scales



What does ReEDS do?

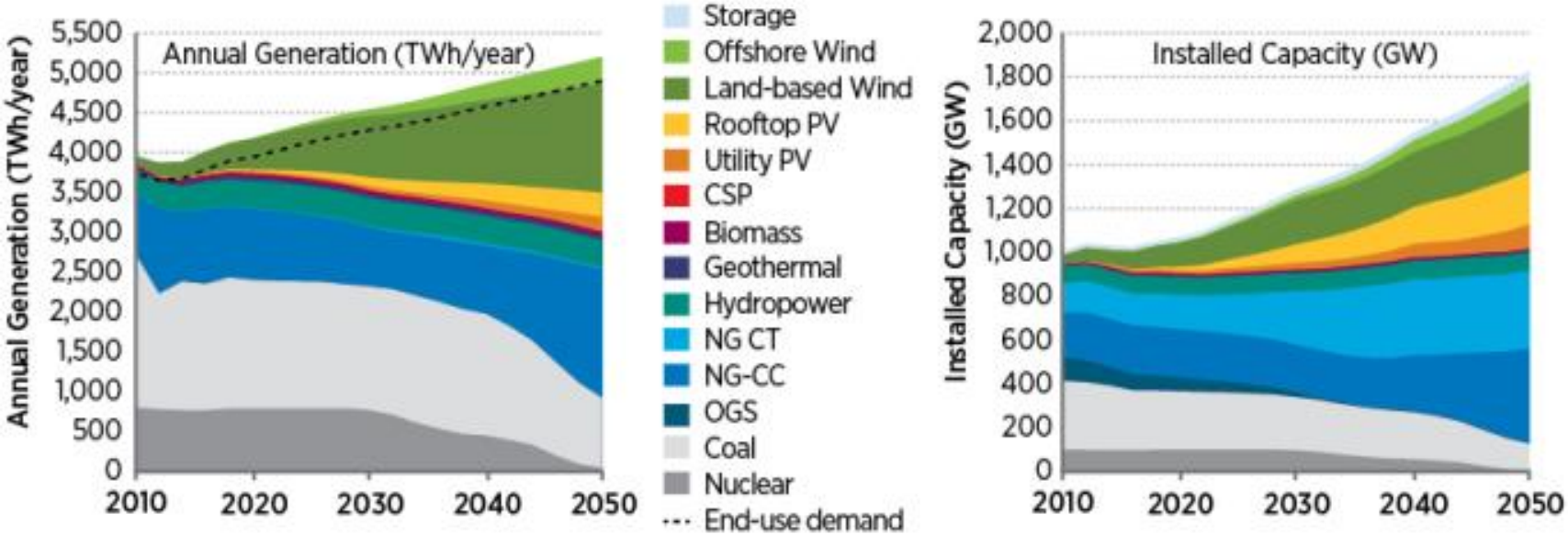
ReEDS generates scenarios of the future U.S. power system



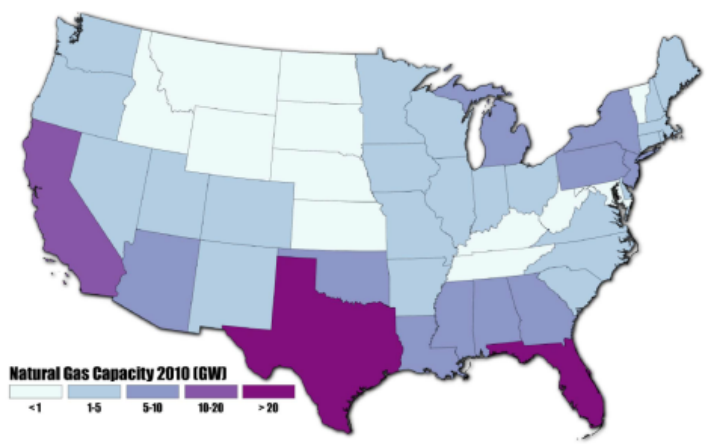
ReEDS finds the regional mix of technologies that meet requirements of the electric sector *at least cost*.

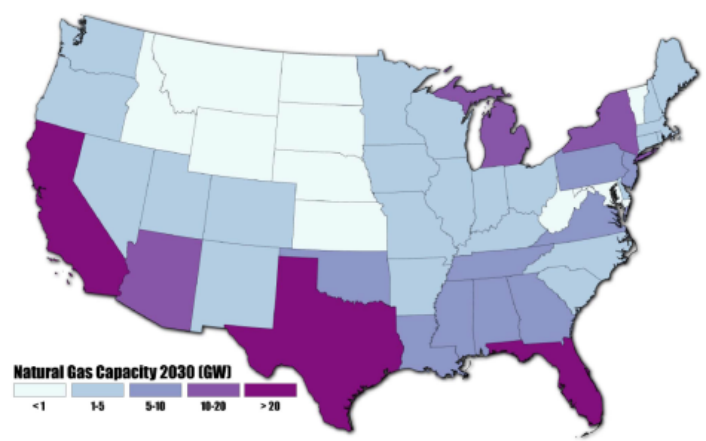
What are the key outputs?

Capacity and generation evolution of all generator types

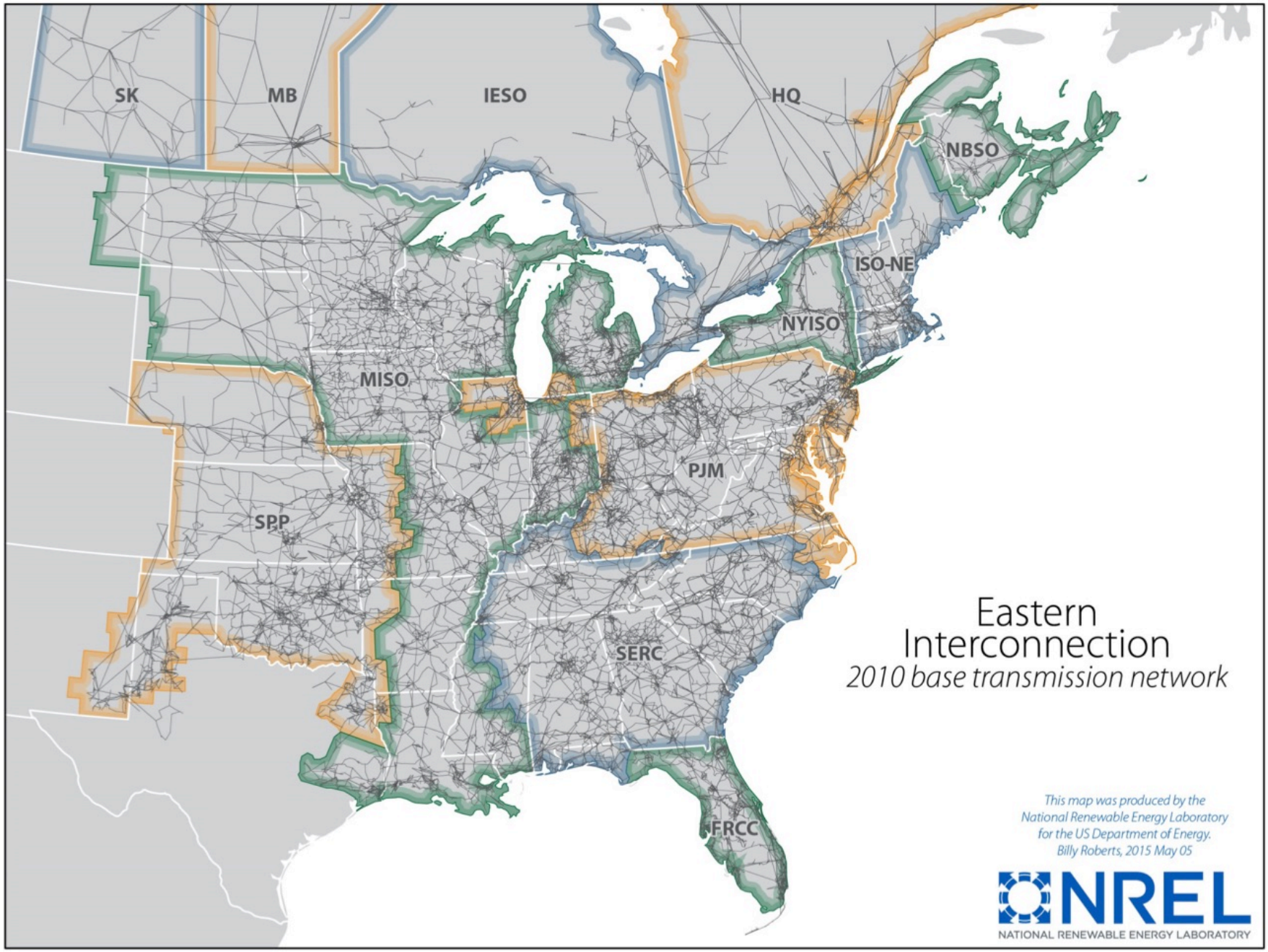


Wind Vision: A New Era for Wind Power (DOE 2015)

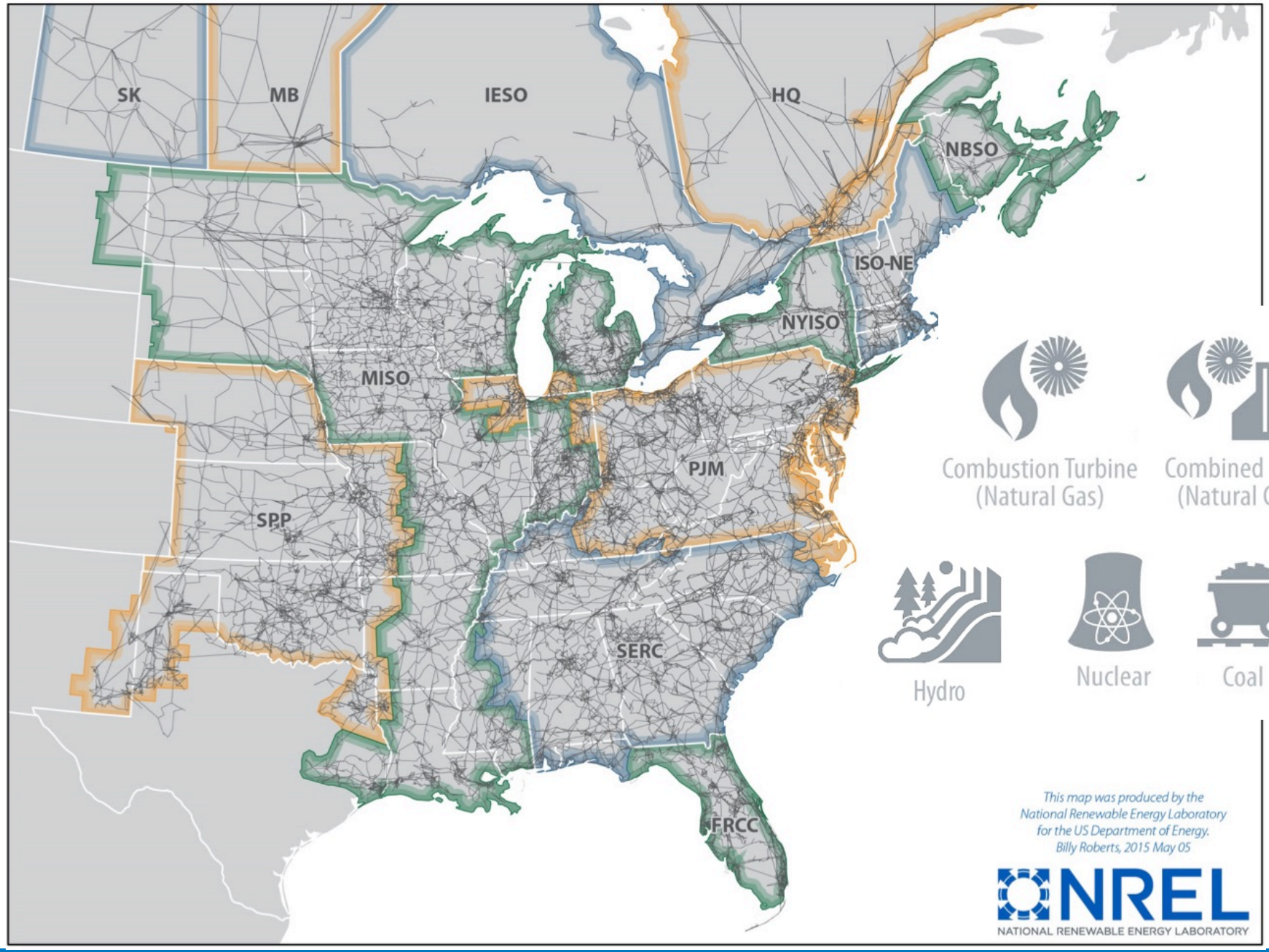




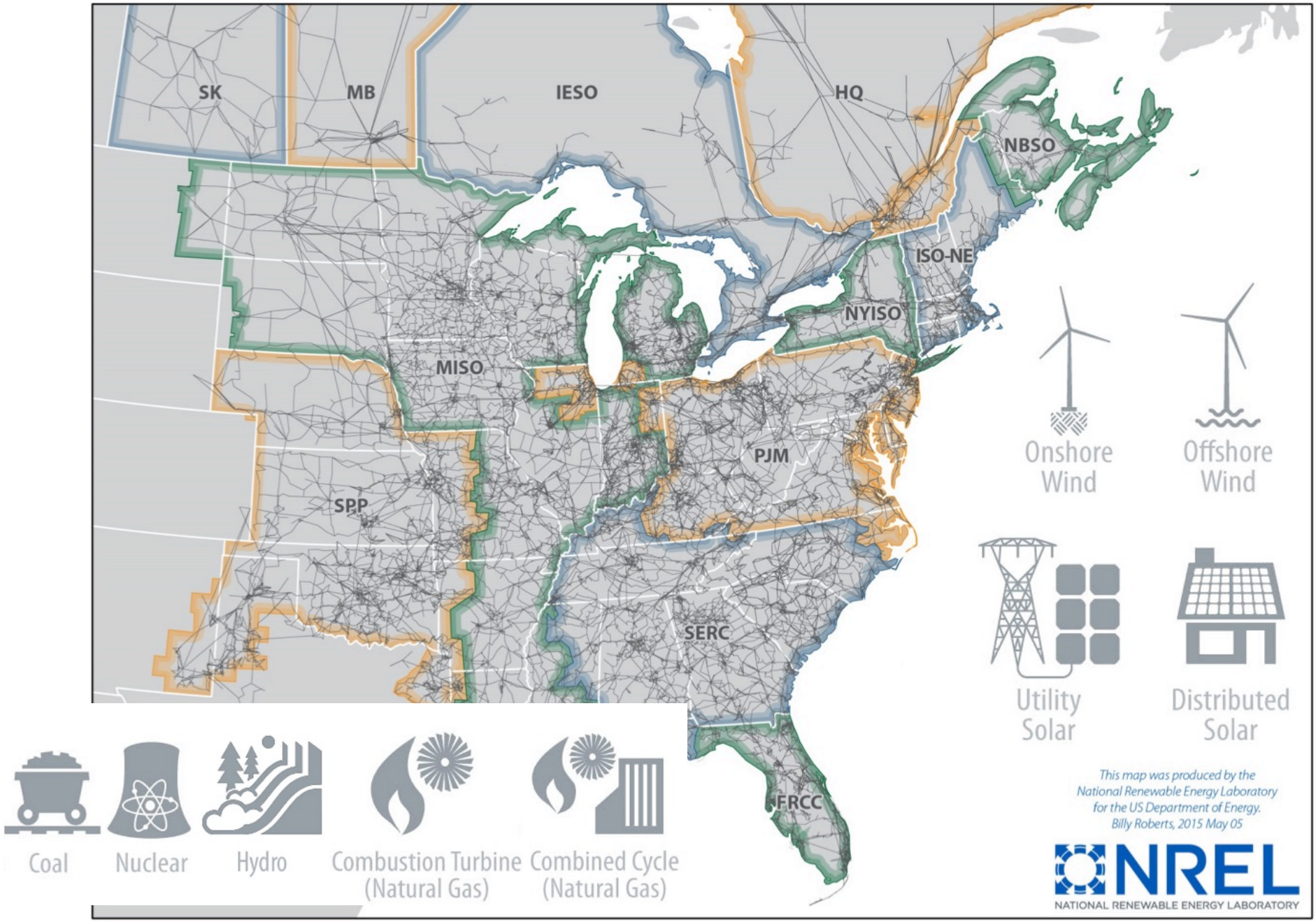
EI- The Largest Coordinated Power System in the World



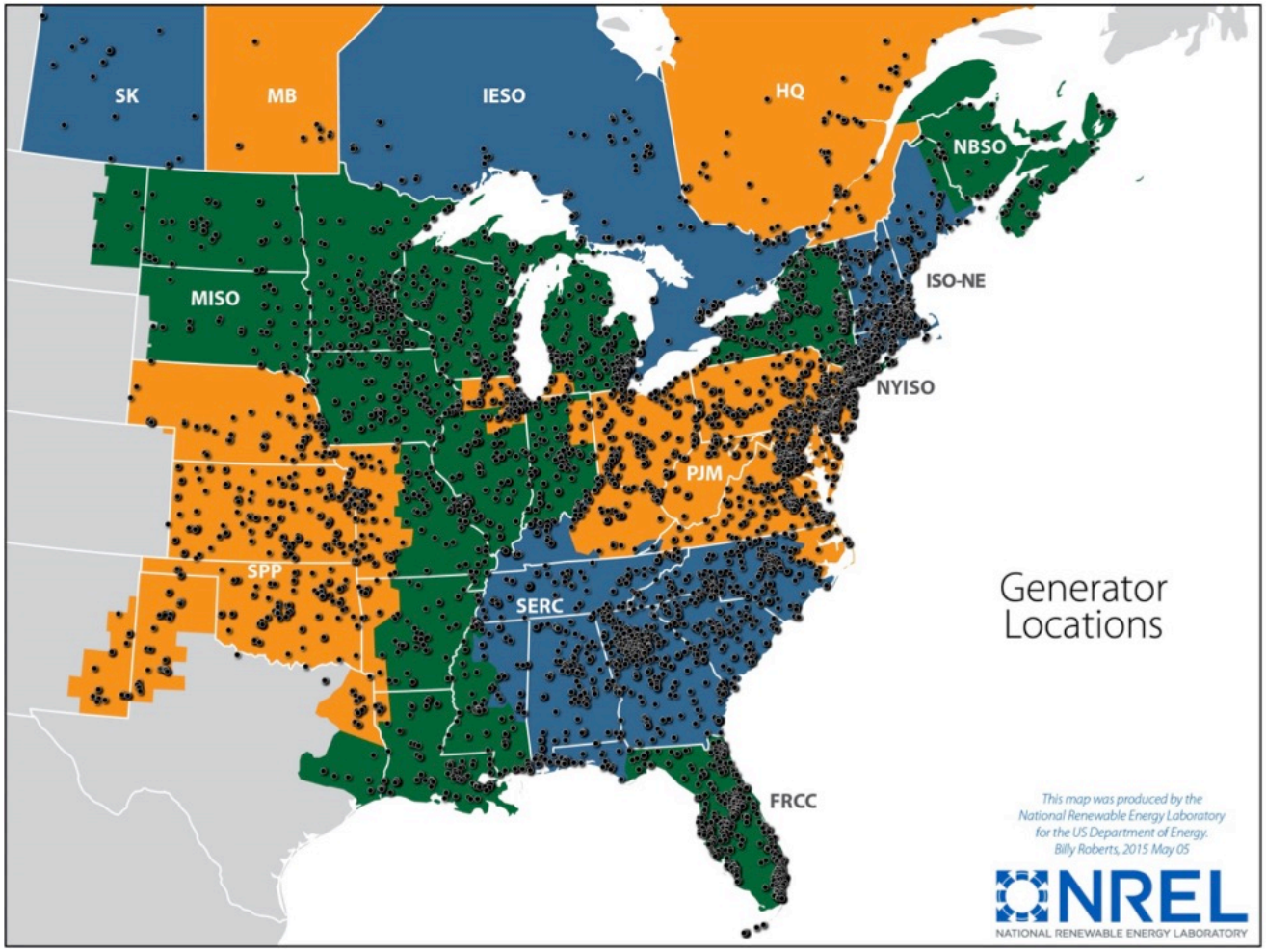
EI- Reliably Designed for Traditional Fuel Sources



EI- Now a System in Transition



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**
  - 50,000 nodes
  - 60,000 transmission lines
  - 5,600 generators
  - 8,760 days
- **Economic Dispatch**
  - Similar formula for 105,120, 5-minute intervals

$$min \sum_t \sum_g (c_g P_{g,t} + c_g^U s_{g,t})$$

$$s.t.$$

$$\theta_n^{min} \leq \theta_{n,t} \leq \theta_n^{max}, \qquad \forall\, n,t$$

$$P_g^{min} u_{g,t} \leq P_{g,t} \leq P_g^{max} u_{g,t}, \qquad \forall\, g,t$$

$$P_k^{min} \leq P_{k,t} \leq P_k^{max}, \qquad \forall\, k,t$$

$$\sum_{i=n} P_{k_{ij},t} - \sum_{j=n} P_{k_{ij},t} - \sum_g P_{n_g,t} - \sum_d P_{n_d,t} = 0, \forall\, n,t$$

$$B_k(\theta_n - \theta_m) - P_{k,t} = 0, \qquad \forall\, k,t$$

$$s_{g,t} - x_{g,t} = u_{g,t} - u_{g,t-1}, \qquad \forall\, g,t$$

$$s_{g,t} \leq 1 - u_{g,t-1}, \qquad \forall\, g,t$$

$$x_{g,t} \leq u_{g,t-1}, \qquad \forall\, g,t$$

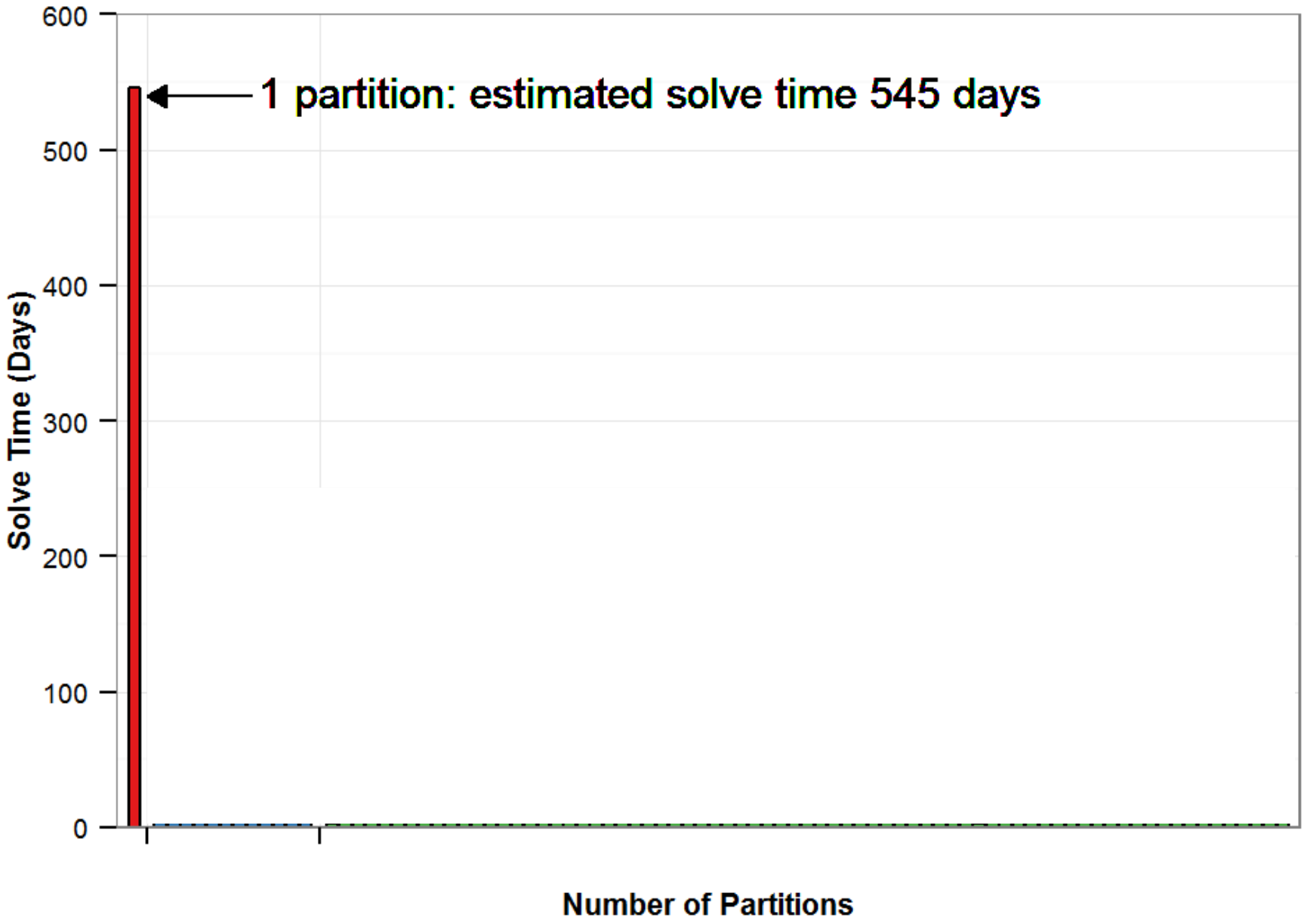
$$u_{g,t} \in \{0,1\} \qquad \forall\, g,t$$

$$x_{g,t} \in \{0,1\} \qquad \forall\, g,t$$

$$s_{g,t} \in \{0,1\} \qquad \forall\, g,t$$

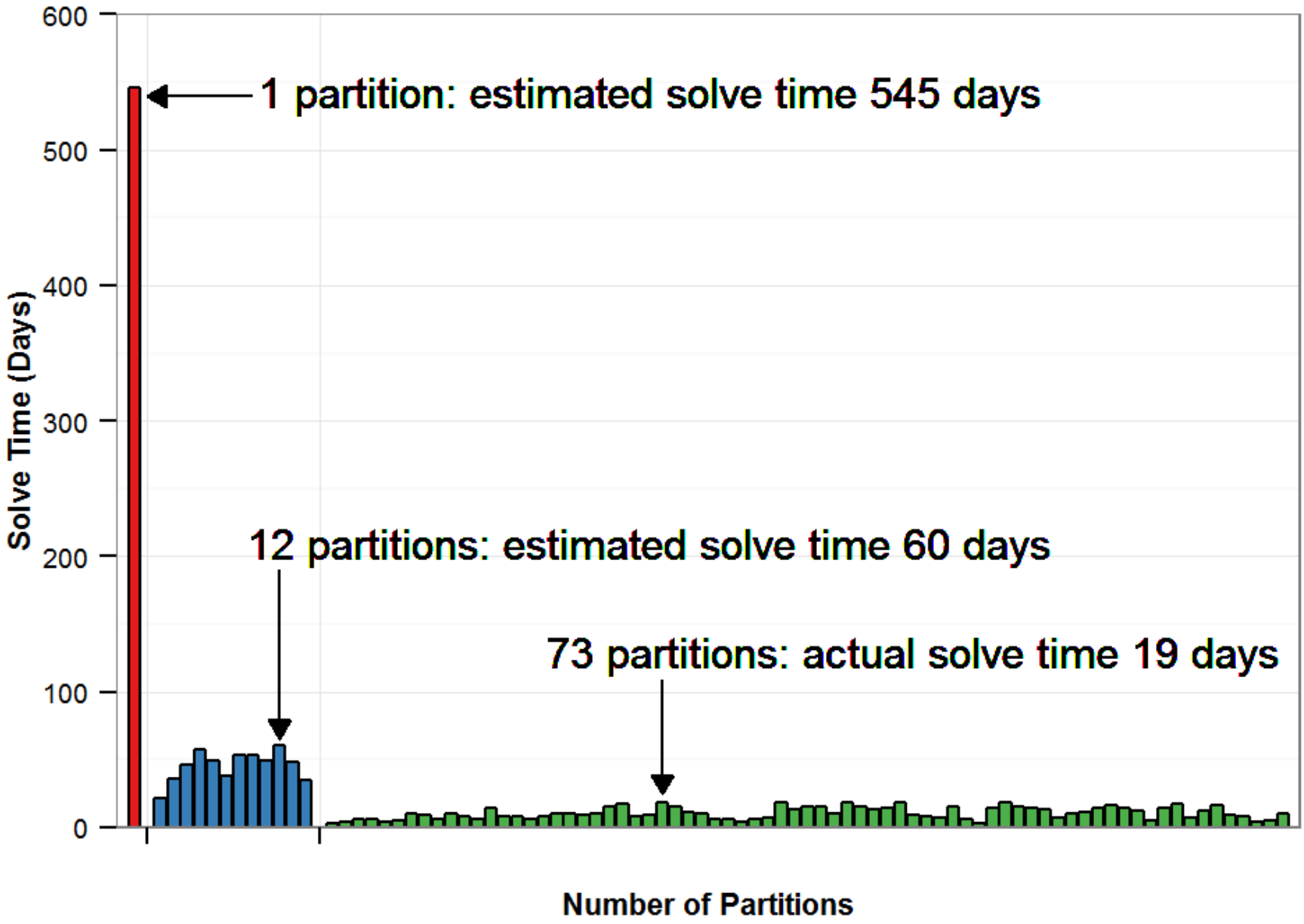
CHALLENGE: Solve for the least cost dispatch over 105,000 times for each scenario.

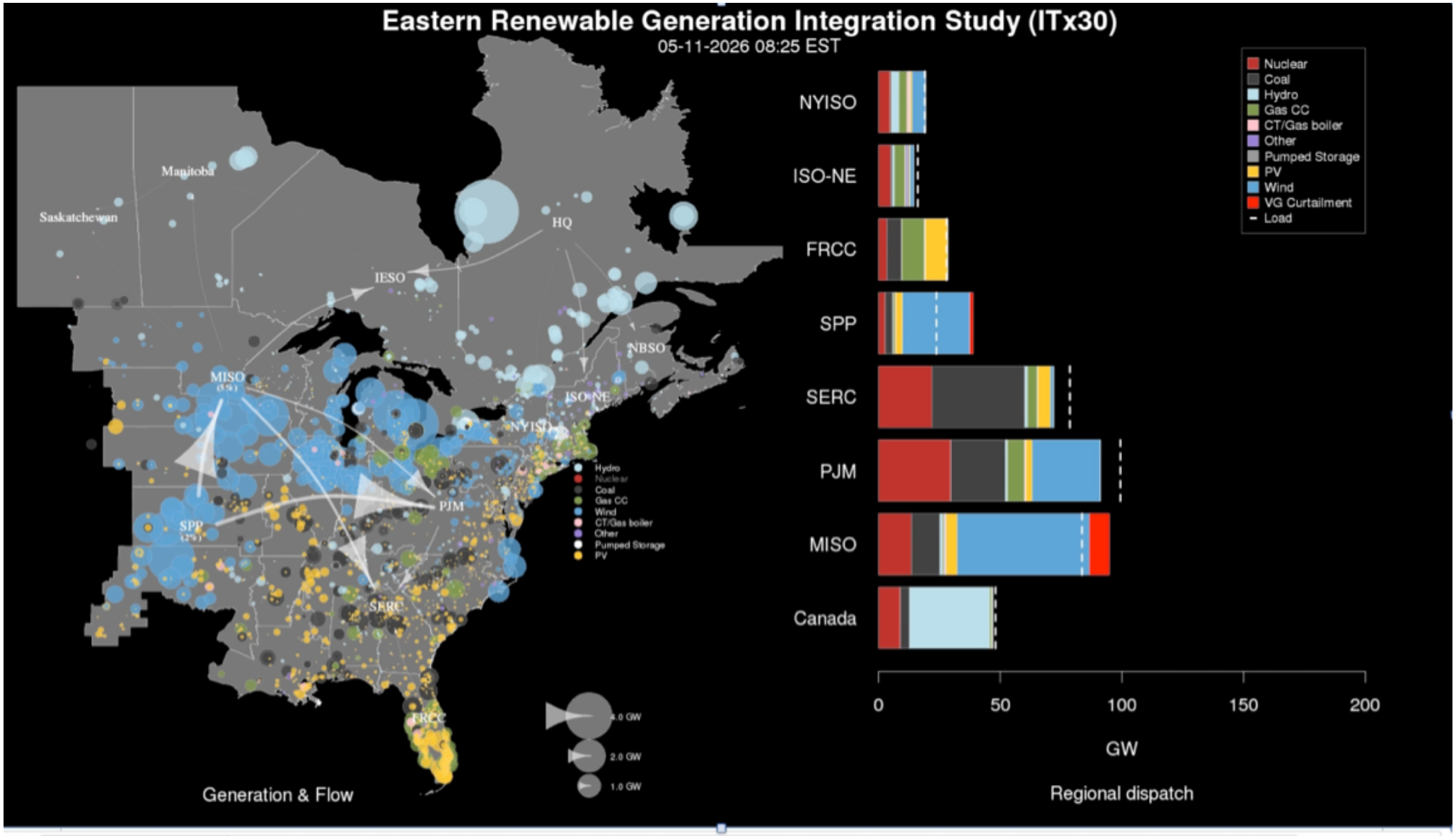
Unit Commitment Problem



Petaflop Problem Solver

Simulation Time Comparison




Eastern Renewable Generation Integration Study (ITx30)
05-11-2026 08:25 EST
Manitoba
Saskatchewan
HQ
IESO
NBSO
MISO
ISO-NE
NYISO
PJM
SPP
SERC
FRCC
Hydro
Nuclear
Coal
Gas CC
Wind
CT/Gas boiler
Other
Pumped Storage
PV
4.0 GW
2.0 GW
1.0 GW
Generation & Flow
NYISO
ISO-NE
FRCC
SPP
SERC
PJM
MISO
Canada
Nuclear
Coal
Hydro
Gas CC
CT/Gas boiler
Other
Pumped Storage
PV
Wind
VG Curtailment
Load
0
50
100
150
200
GW
Regional dispatch

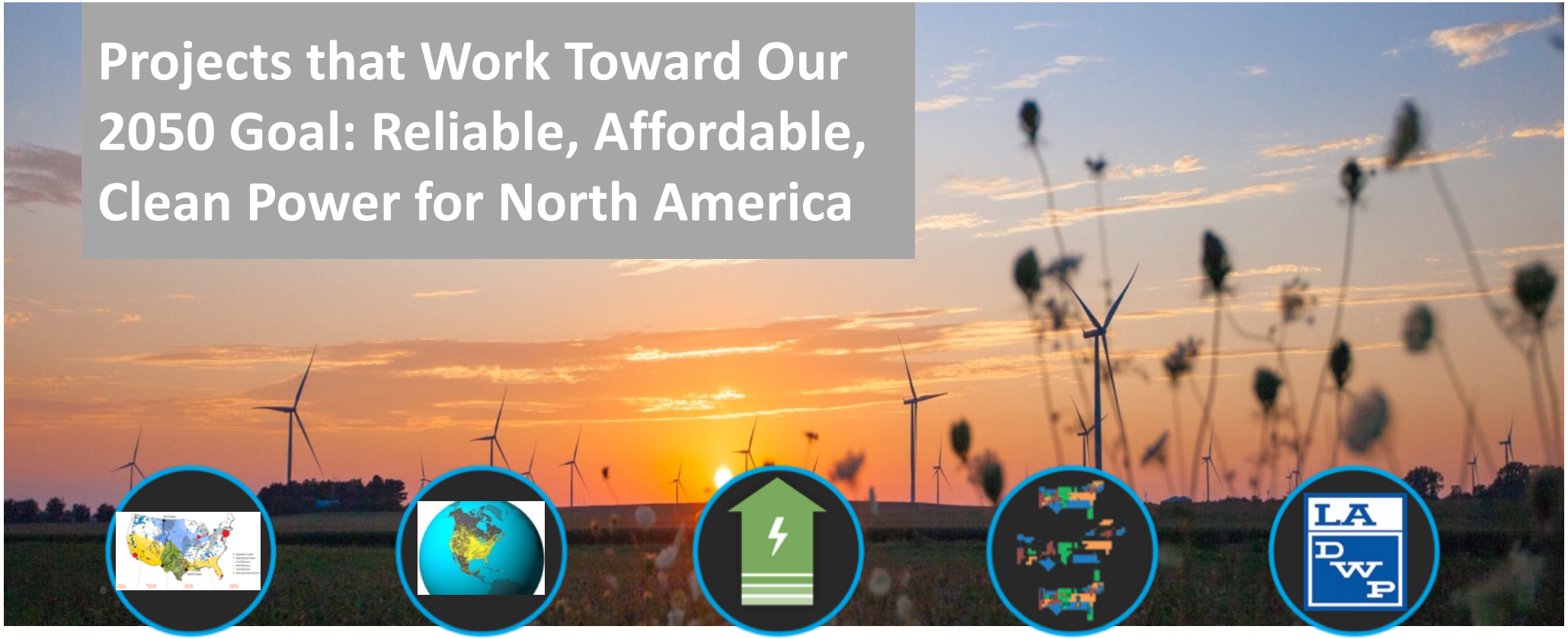
00:18.72

ERGIS Visualization

- 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?

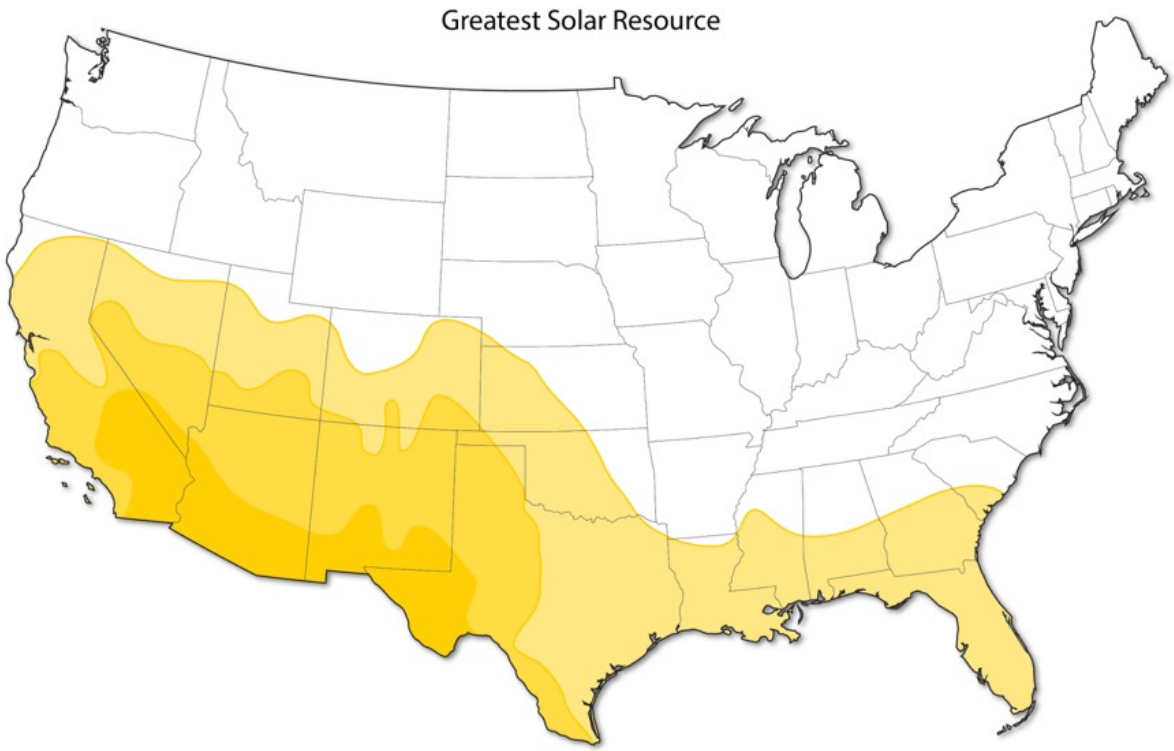
October 2018

Los Angeles 100%

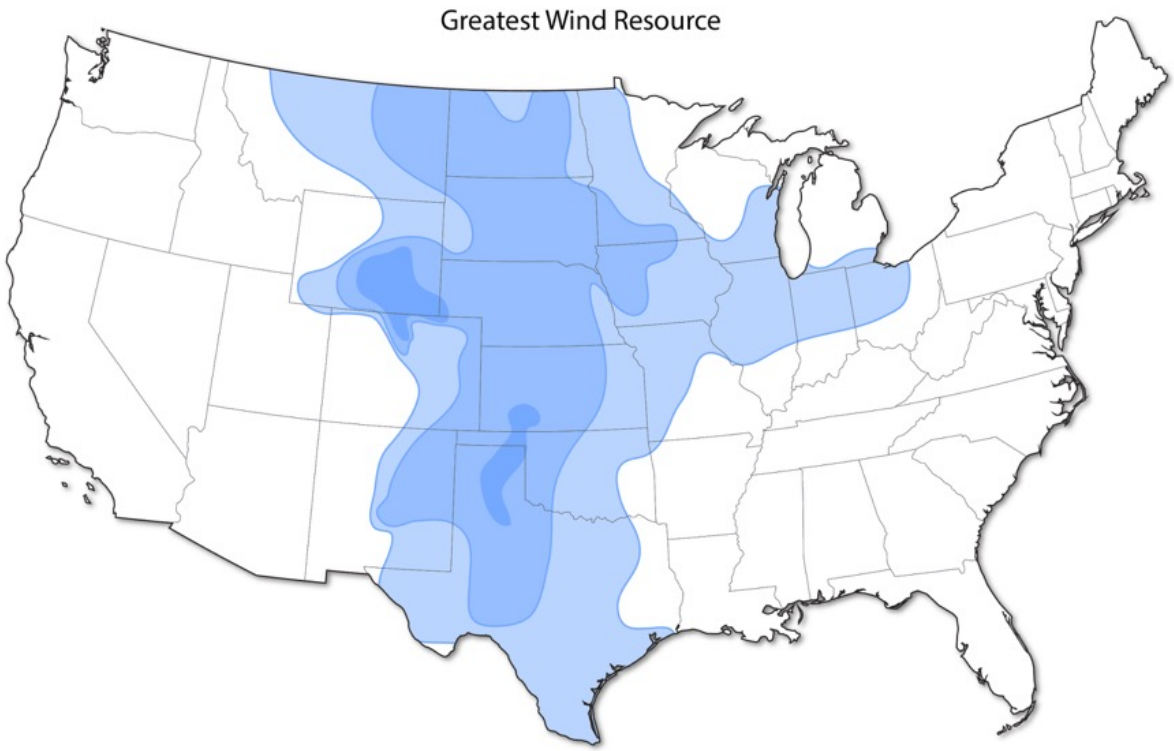
Can LA operate on 100% Renewable Energy

July 2020

The U.S. has Diverse Resources and Demand

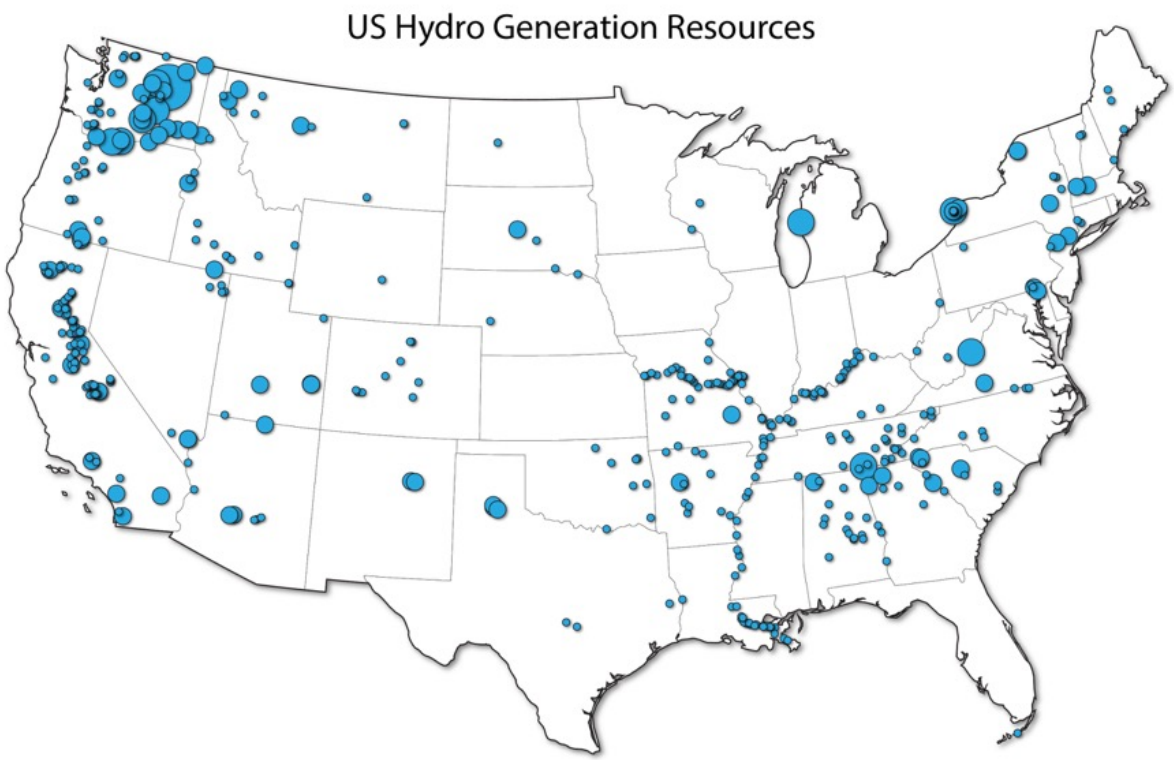


The U.S. has Diverse Resources and Demand

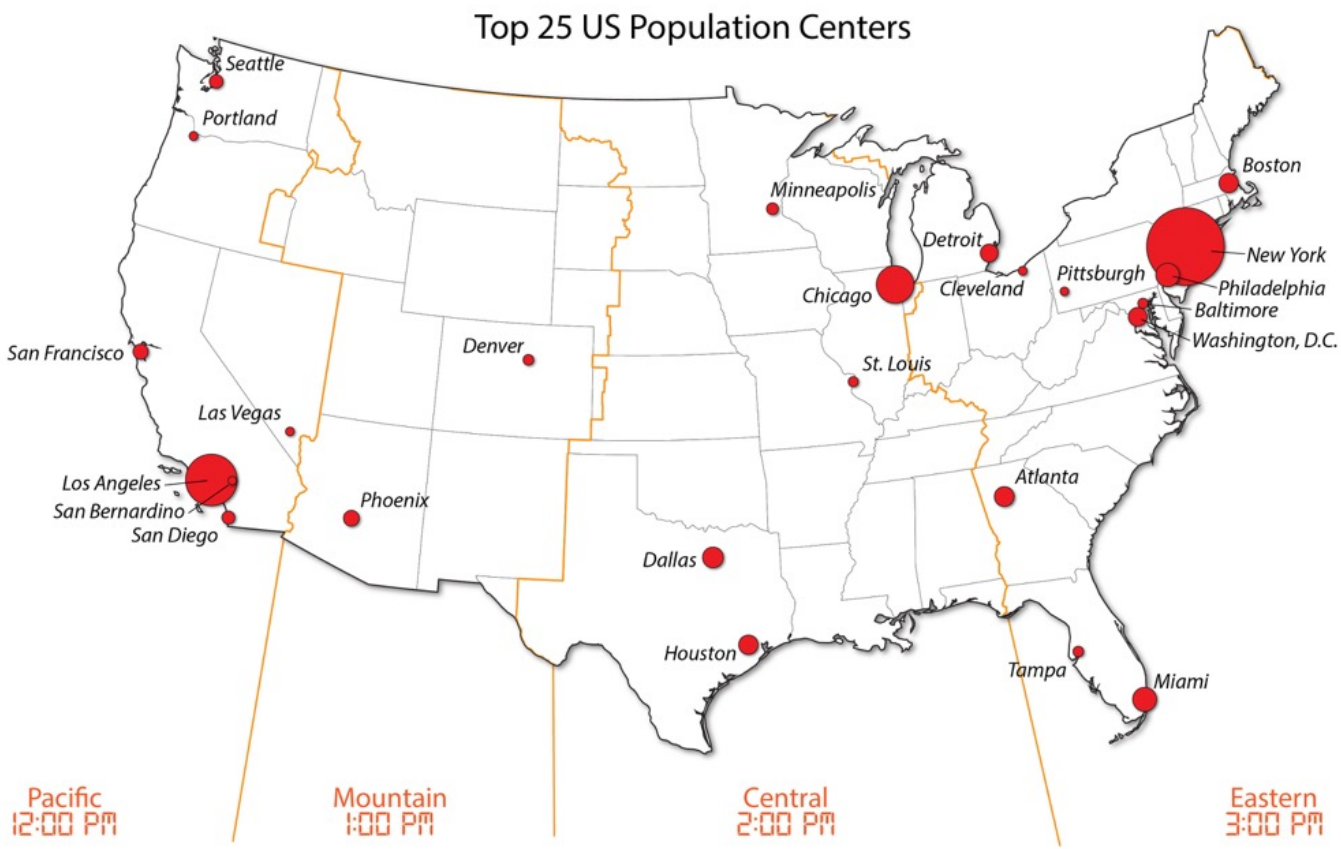


The U.S. has Diverse Resources and Demand

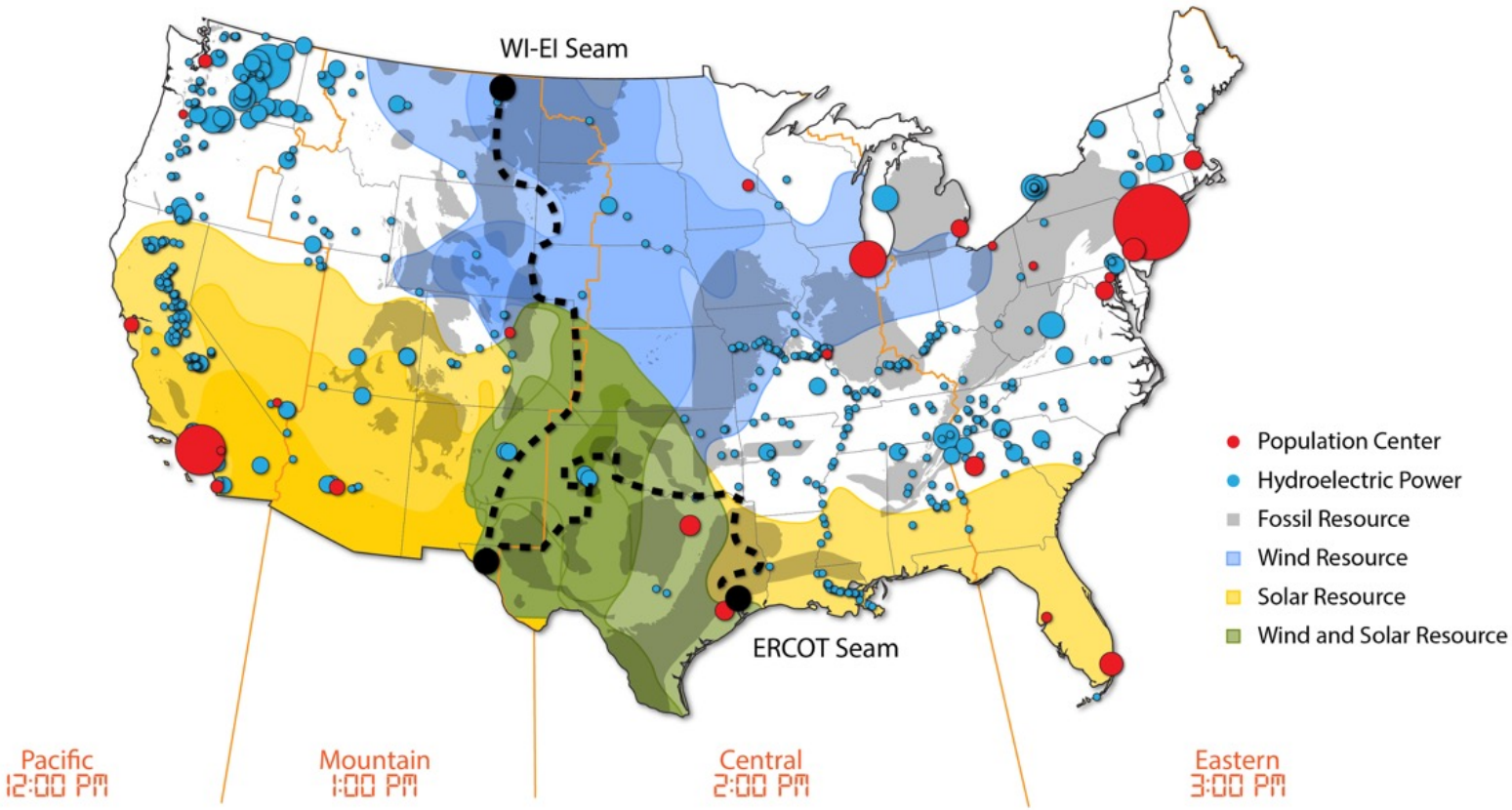
The U.S. has Diverse Resources and Demand



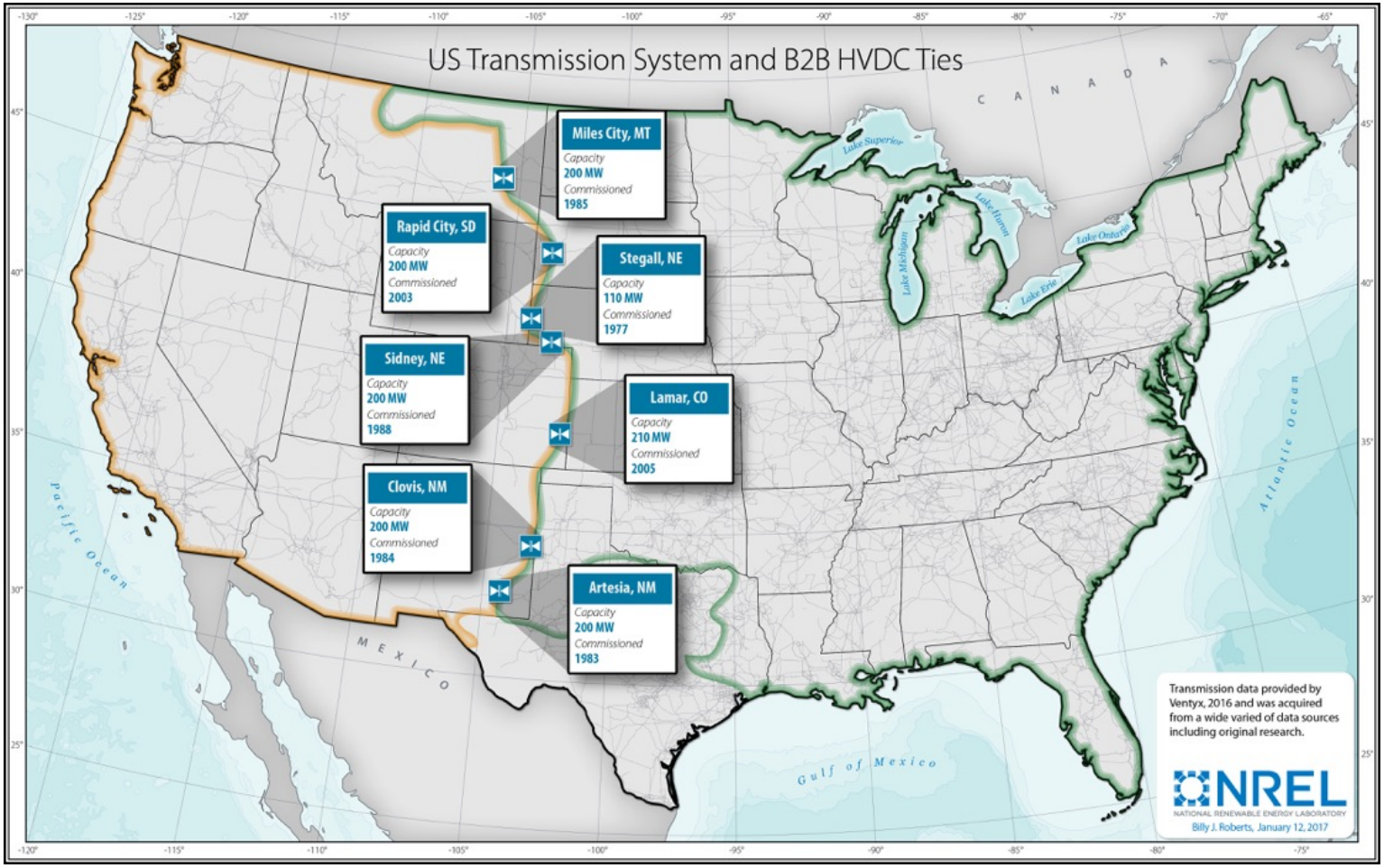
The U.S. has Diverse Resources and Demand



The U.S. has Diverse Resources and Demand



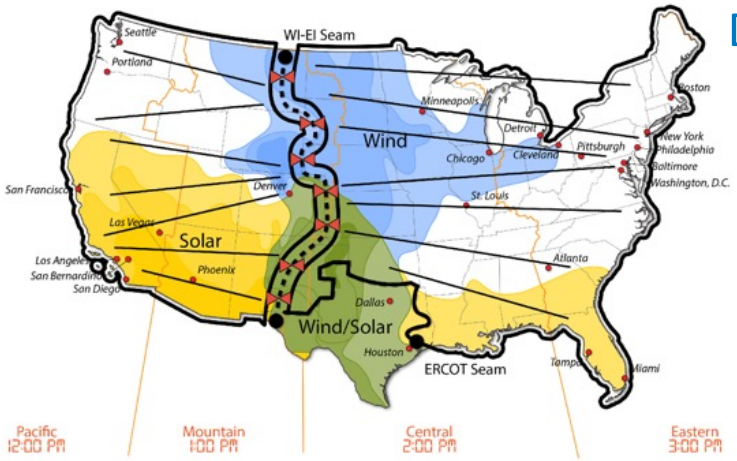
The East/West Seam



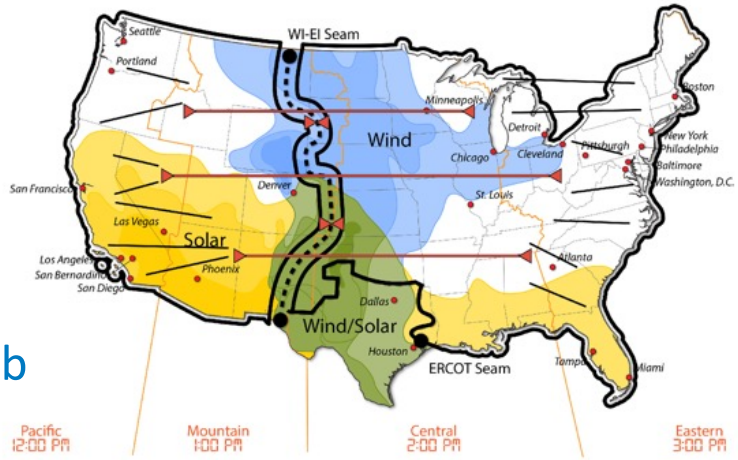
Identifying the Value of Cross Seam Transmission

Design 1

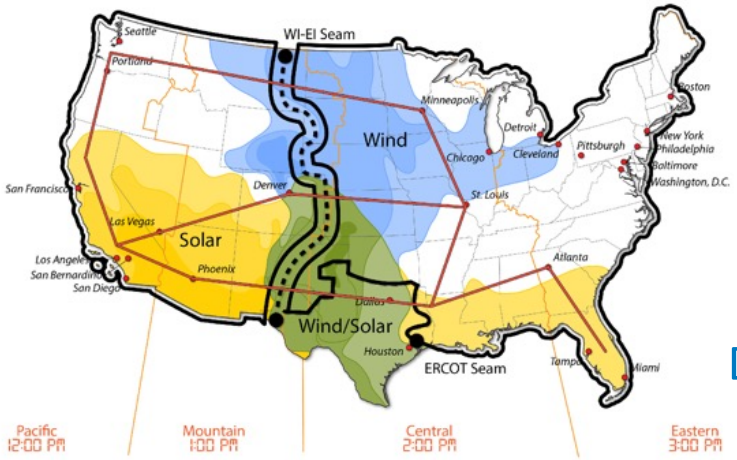
Design 2a



Design 2b



Design 3



Preliminary (Unpublished) Results

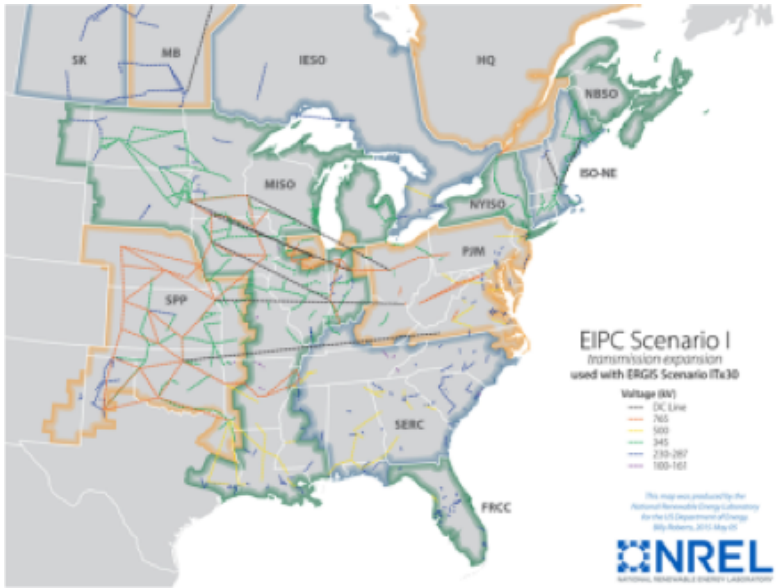
ECONOMICS, NPV $B	Design 1	Delta 2a	Delta 2b	Delta 3b
Line Investment Cost	61.21	12.68	13.67	18.89
Total non-Transmission Costs	2,211.49	-31.54	-45.17	-47.77
Benefit to Cost Ratio		2.49	3.3	2.53

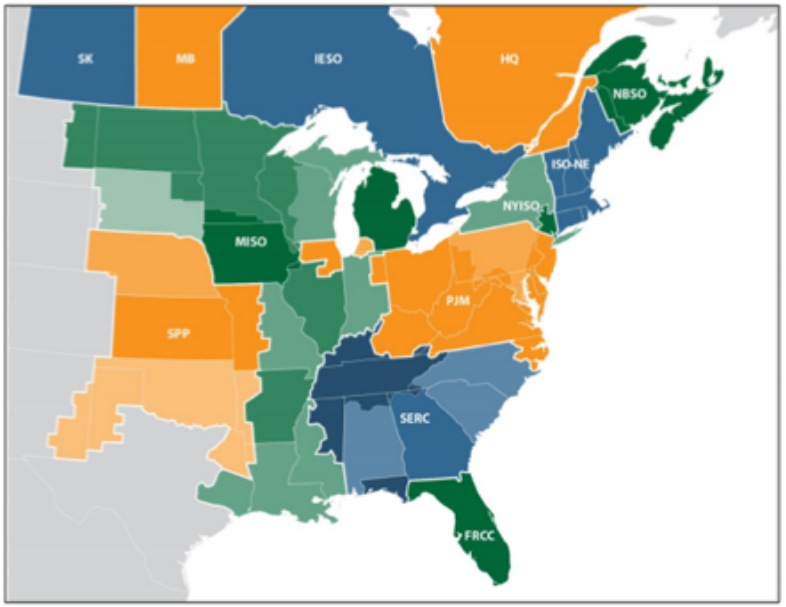
- Study evaluates trillions of dollars in investments
- Annual benefits are in the 10s of billions of dollars
- All transmission expansions pay for themselves in 15 years (2024-2038), over the life of the asset the value could be much larger
- Clearly there is a value to increased transmission connections between the east and west
- RESULT PRELIMINARY - DO NOT CITE

REFutures in the East: Base Scenario

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

- 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

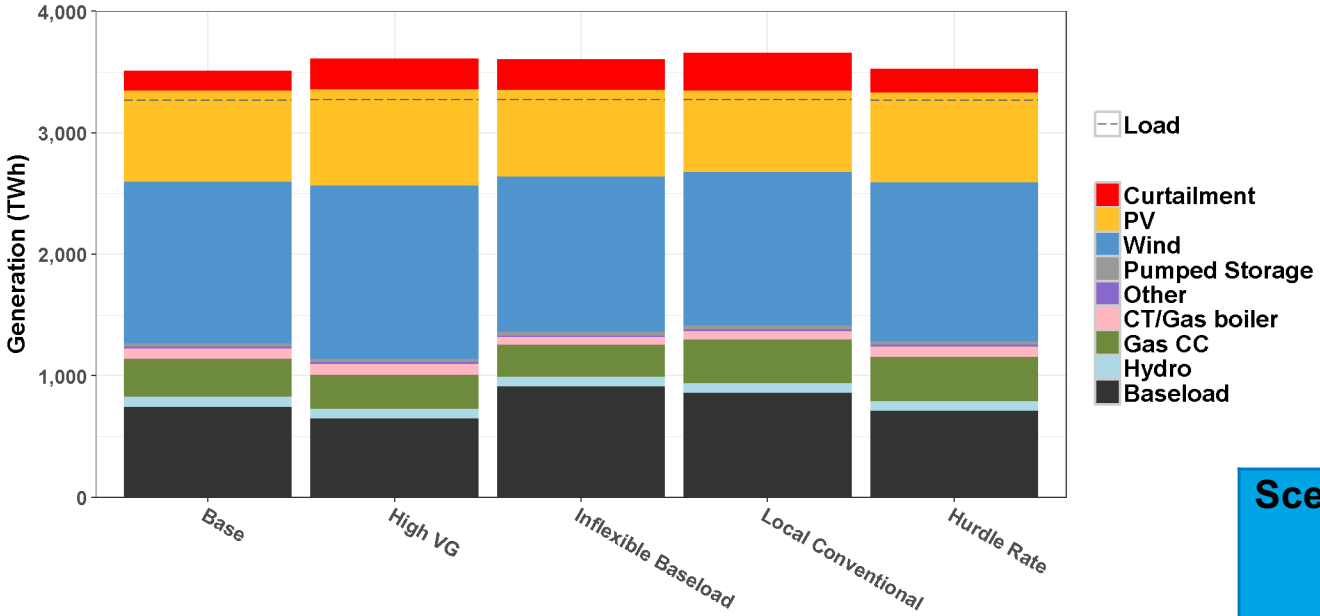


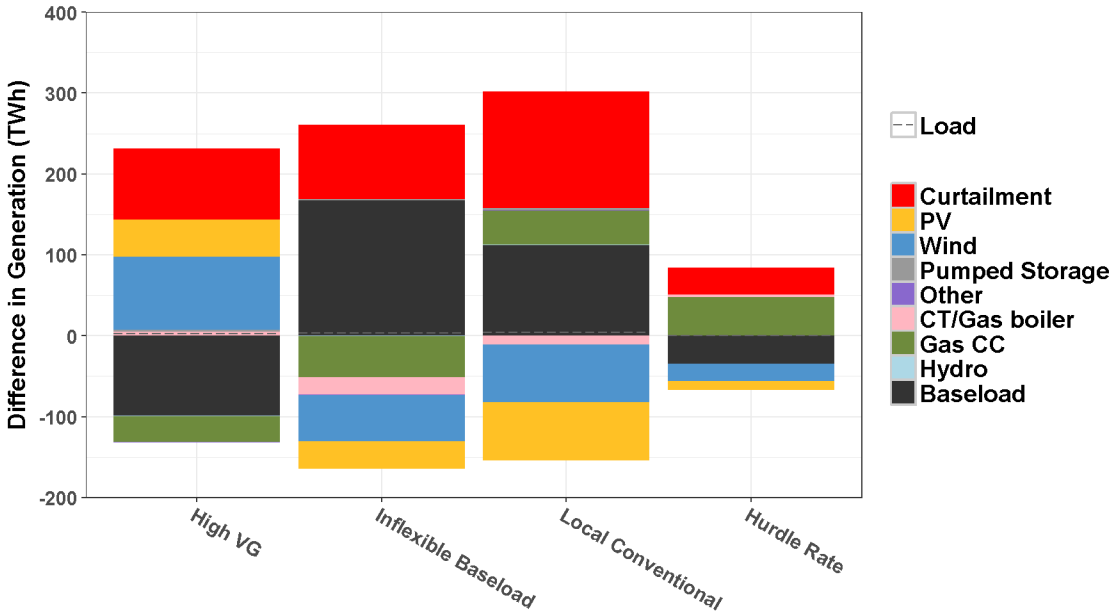


Scenarios

Base	High VG	Hurdle Rate	Inflexible Baseload	Local Conventional
➢ ERGIS Thermal and Hydro Assumptions ➢ ERGIS ITx30 Transmission ➢ 76% RE, 74% VG VG (pre-curtailment) ➢ Nuclear units retired ➢ Baseload units (all ERGIS coal units) have coal flexibility	➢ 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

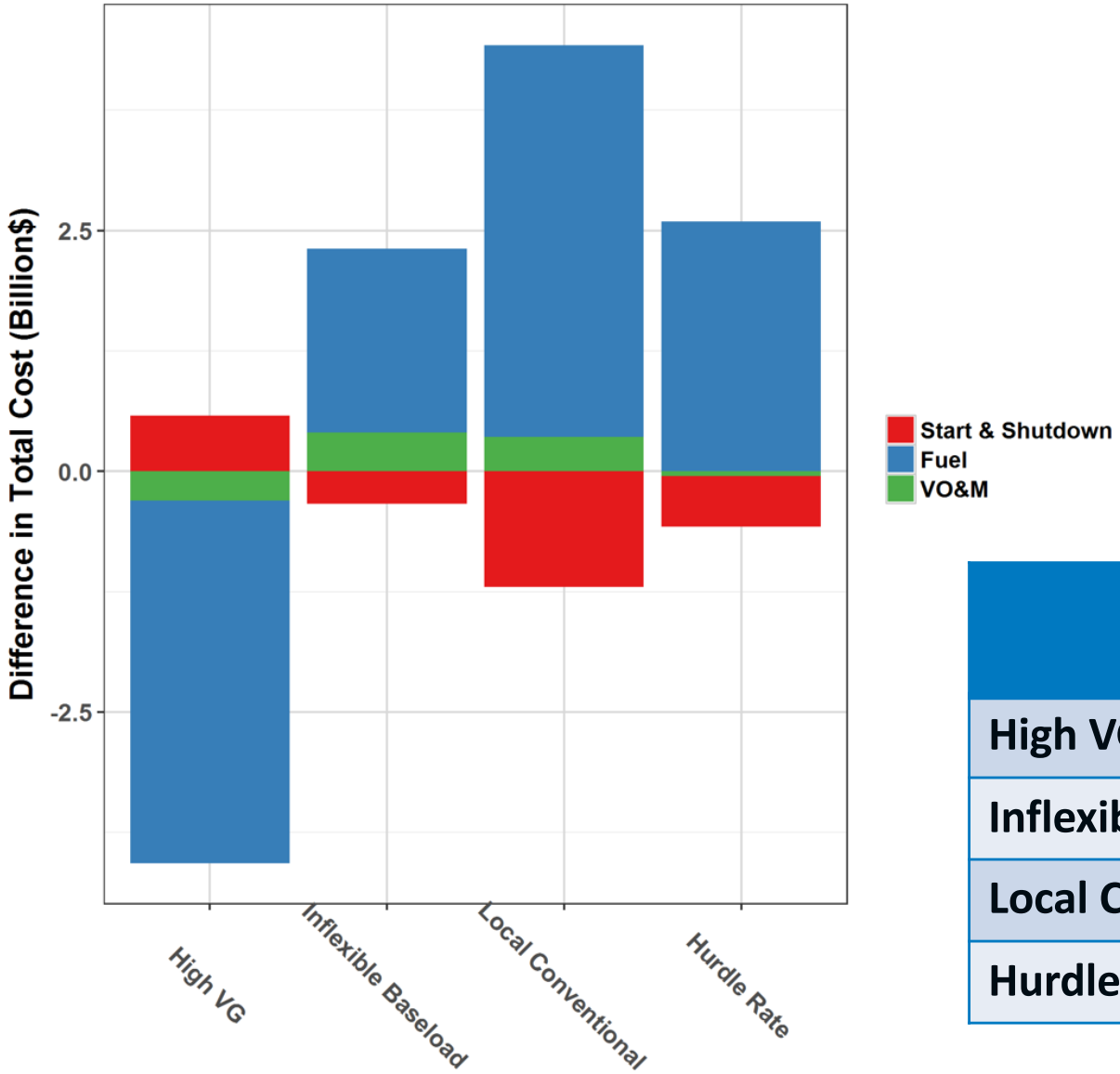
U.S. EI curtailment ranges from 7-14%





Scenario	VG curtailment
Base	7.3%
High VG	10.2%
Inflexible Baseload	11.4%
Local Conventional	13.7%
Hurdle Rate	8.8%

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.

	% Difference from Base Scenario
High VG	-7%
Inflexible Baseload	4%
Local Conventional	7%
Hurdle Rate	4%

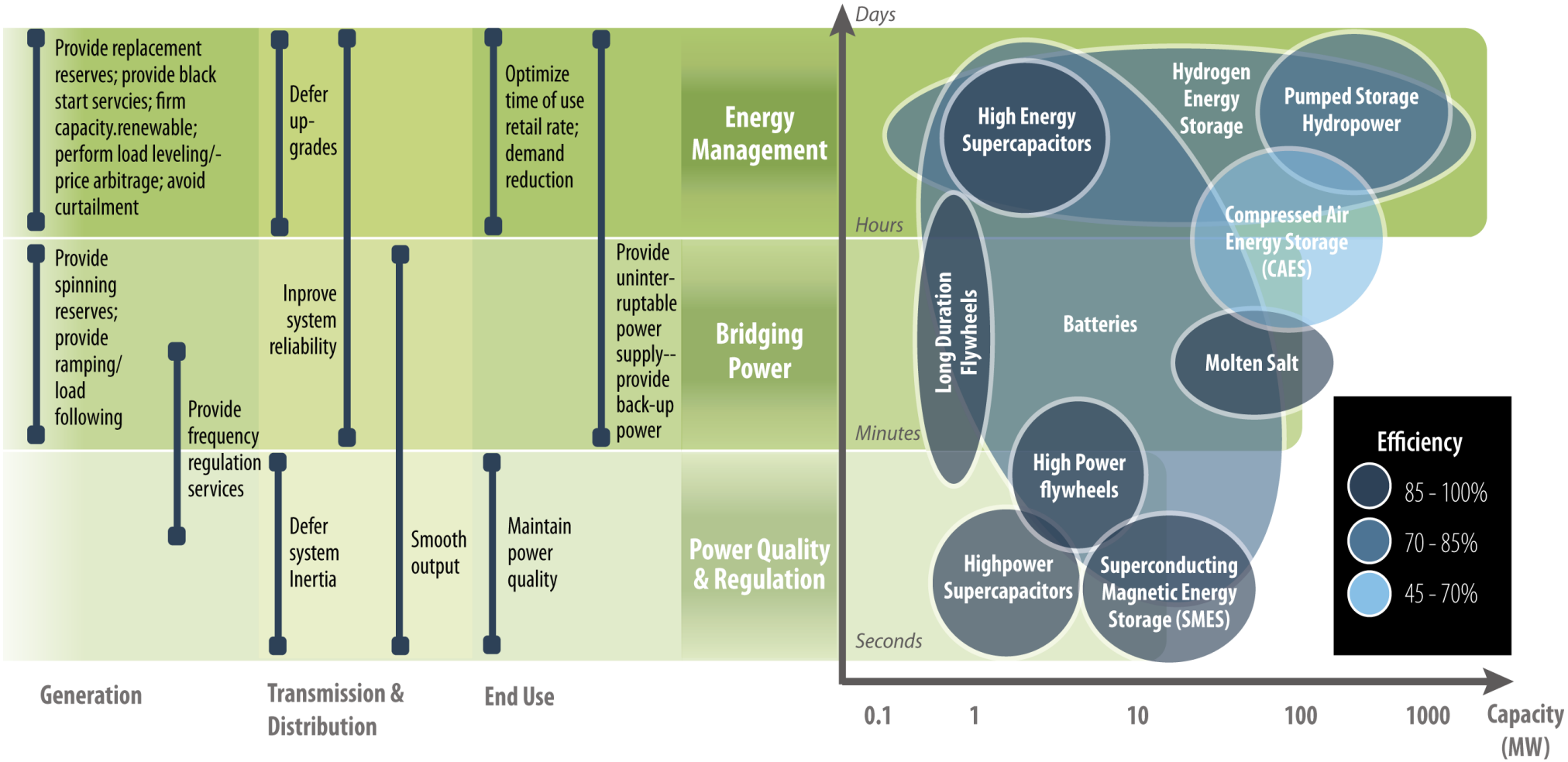
Conclusions

- 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

Grid Application Depends on Storage Characteristics



Different technologies can address different grid needs, but no single storage technology, in the near term, is likely to meet all grid applications.

Li-Ion Status

Utility DIVE Home Events Library Jobs Viewpoints Topics

Tesla has 100 days to build a 129 MWh storage plant in South Australia

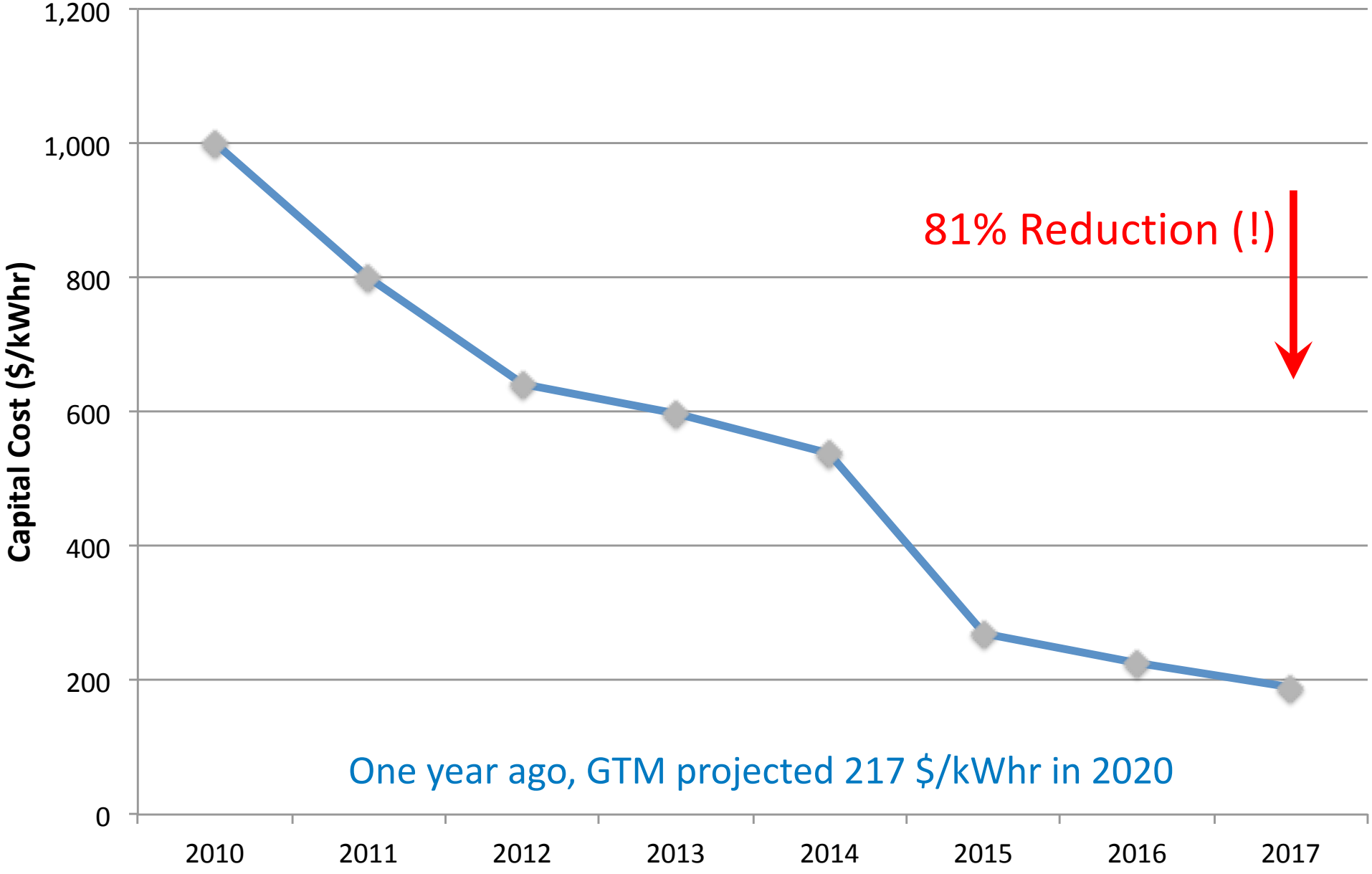
AUTHOR
Peter Maloney
@TopFloorPower

PUBLISHED
July 10, 2017

Dive Brief:

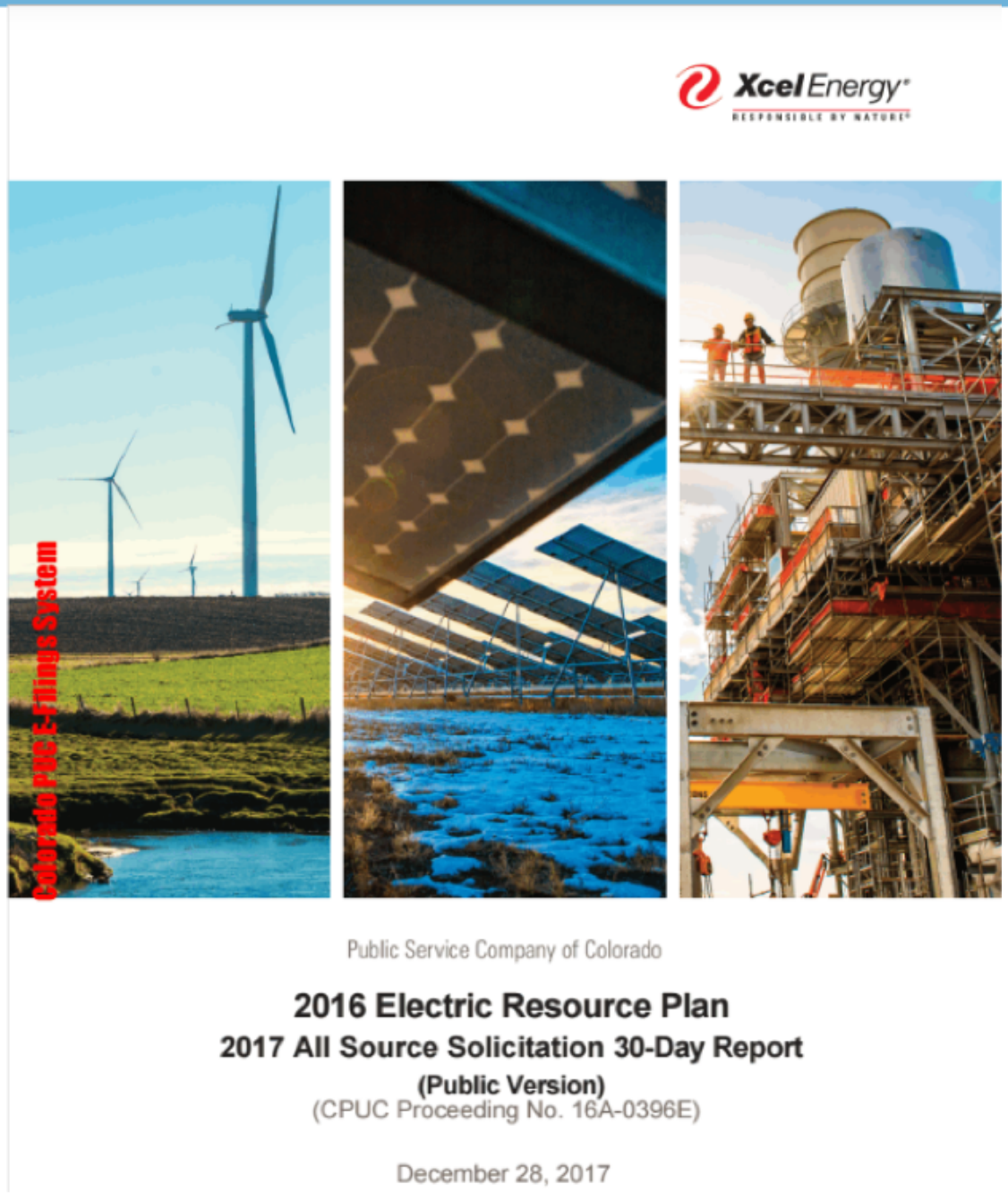
- South Australia Premier Jay Weatherill last week announced that Tesla has won a solicitation to build a 100 MW, 129 MWh energy storage project at a wind farm operated by Neoen of France.
- The storage facility will be "built and working" within 100 days of contract signature or it will be free, keeping 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.

Li-Ion Status



Electrek.com

Late-breaking Xcel News



Xcel RFP Responses

RFP Responses by Technology

Generation Technology	# of Bids	Bid MW	# of Projects	Project MW	Median Bid Price or Equivalent	Pricing Units
Combustion Turbine/IC Engines	30	7,141	13	2,466	$ 4.80	$/kW-mo
Combustion Turbine with Battery Storage	7	804	3	476	6.20	$/kW-mo
Gas-Fired Combined Cycles	2	451	2	451		$/kW-mo
Stand-alone Battery Storage	28	2,143	21	1,614	11.30	$/kW-mo
Compressed Air Energy Storage	1	317	1	317		$/kW-mo
Wind	96	42,278	42	17,380	$ 18.10	$/MWh
Wind and Solar	5	2,612	4	2,162	19.90	$/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	111,963	238	58,283		

Thanks!

david.mooney@nrel.gov

www.nrel.gov

NREL

NATIONAL RENEWABLE ENERGY LABORATORY