Electricity Market Design with Variable Renewable Generation: A U.S. Perspective

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Outline

- Current Status in the United States
  - Renewable Energy Expansion
  - Impacts on Market Prices
  - Electricity Market Design
- Flexibility Solutions for Electricity Markets with Higher Shares of Renewable Energy
  - Dynamic operating reserves
  - Renewables providing reserves
  - Energy storage
  - Nuclear flexibility
- Concluding Remarks

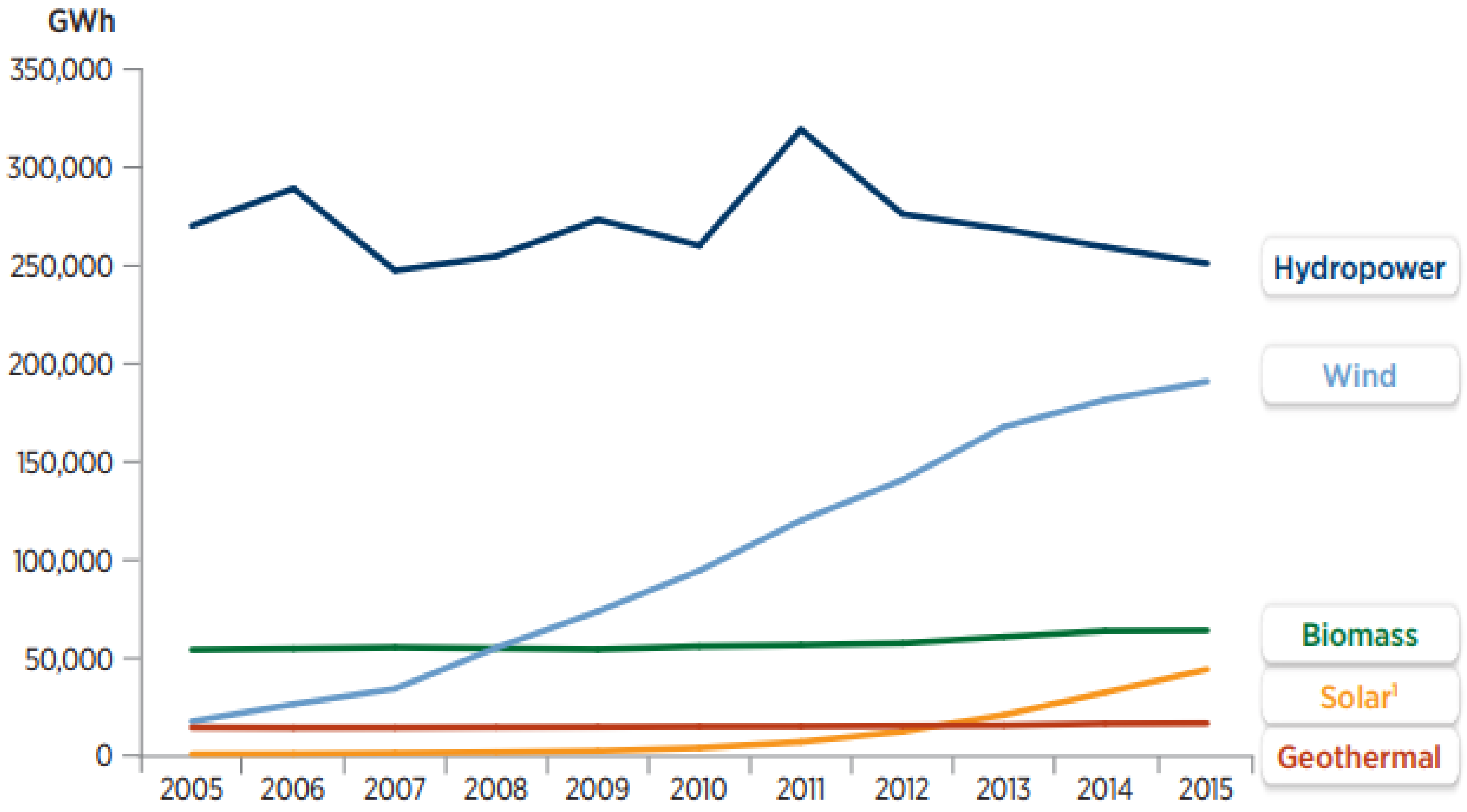
A Changing Fuel Mix

U.S. Electricity Generation by Source

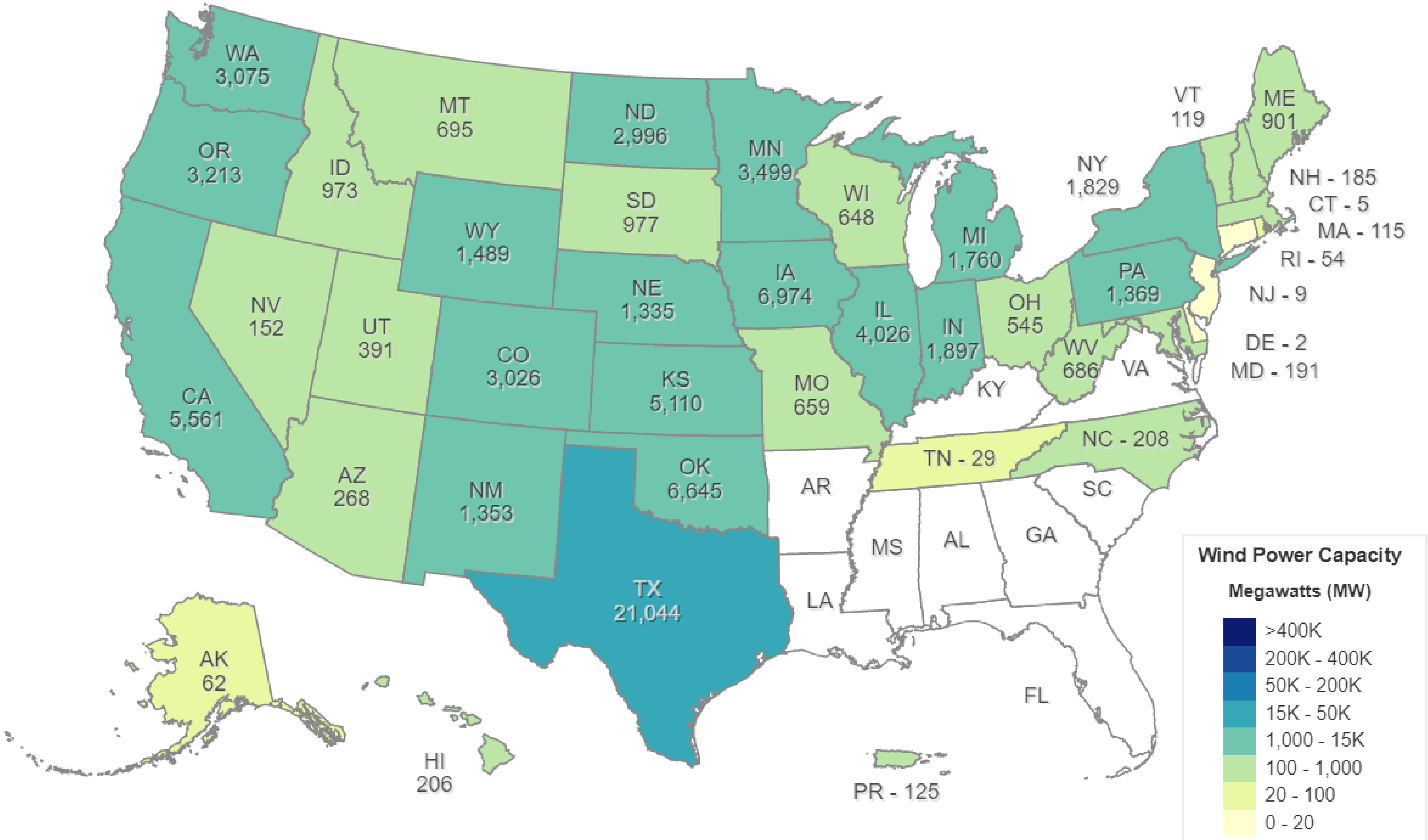
	Coal	Petroleum Liquids	Petroleum Coke	Natural Gas	Other Gases	Nuclear	Renewables[1]	Other	Total Generation (GWh)
2005	49.5%	2.5%	0.6%	18.7%	0.3%	19.2%	8.8%	0.3%	4,062,573
2006	48.9%	1.1%	0.5%	20.0%	0.3%	19.3%	9.5%	0.3%	4,072,064
2007	48.4%	1.2%	0.4%	21.5%	0.3%	19.4%	8.5%	0.3%	4,164,734
2008	48.1%	0.8%	0.3%	21.4%	0.3%	19.5%	9.3%	0.3%	4,126,985
2009	44.4%	0.7%	0.3%	23.3%	0.3%	20.2%	10.6%	0.3%	3,956,872
2010	44.7%	0.6%	0.3%	23.9%	0.3%	19.5%	10.4%	0.3%	4,133,667
2011	42.2%	0.4%	0.3%	24.7%	0.3%	19.2%	12.6%	0.3%	4,112,099
2012	37.3%	0.3%	0.2%	30.2%	0.3%	18.9%	12.4%	0.3%	4,061,061
2013	38.7%	0.3%	0.3%	27.6%	0.3%	19.3%	13.1%	0.3%	4,082,687
2014	38.4%	0.4%	0.3%	27.4%	0.3%	19.4%	13.5%	0.3%	4,115,446
2015	33.0%	0.4%	0.3%	32.5%	0.3%	19.4%	13.8%	0.3%	4,110,296

Growth In Wind and Solar Generation

U.S. Renewable Electricity Generation by Technology



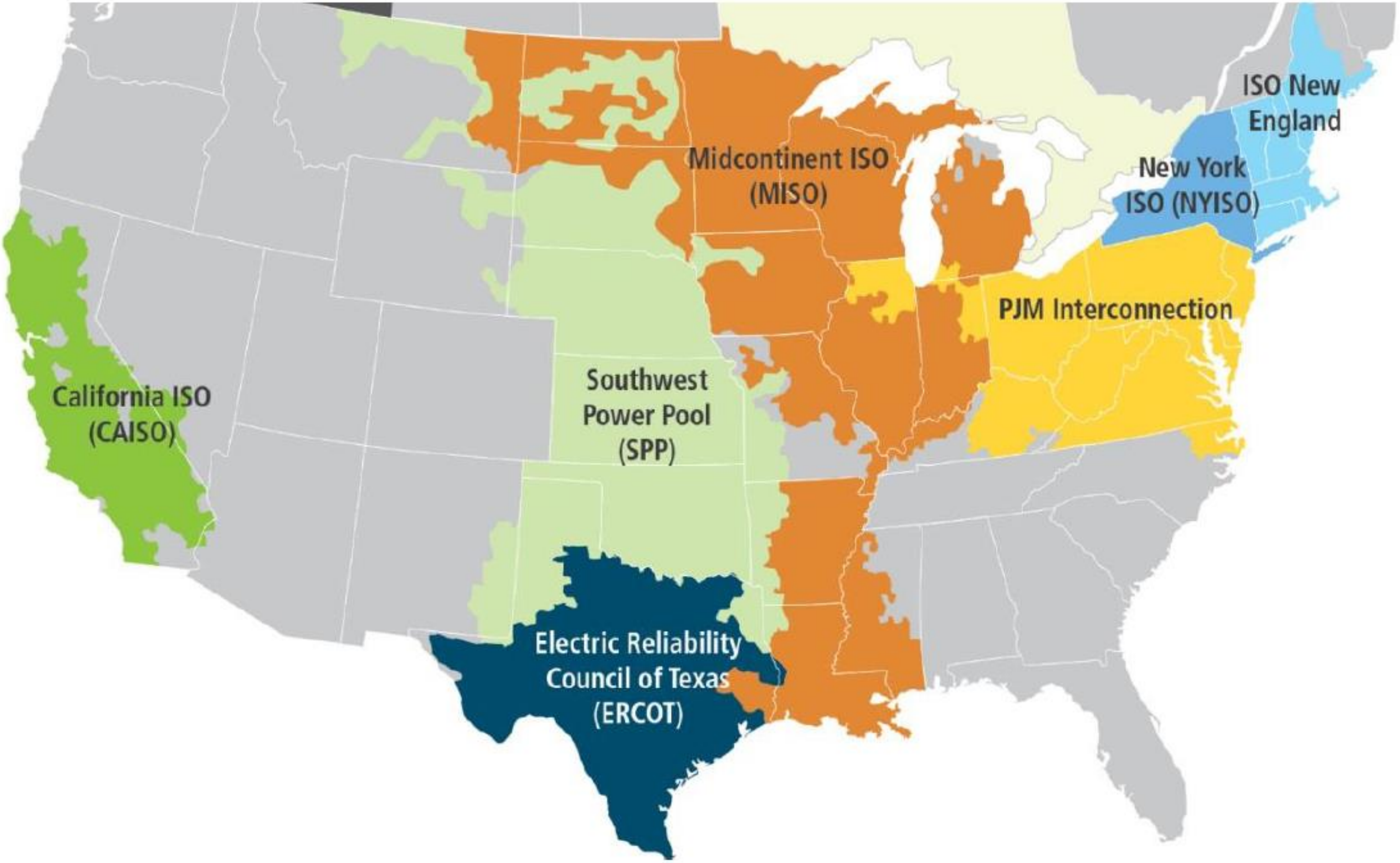
Installed Wind Power Capacity by State (Q2 2017)



Total Installed Wind Capacity: 84,407 MW

Source: American Wind Energy Association Market Report

Electricity Markets in the United States



Electricity Markets and Reliability

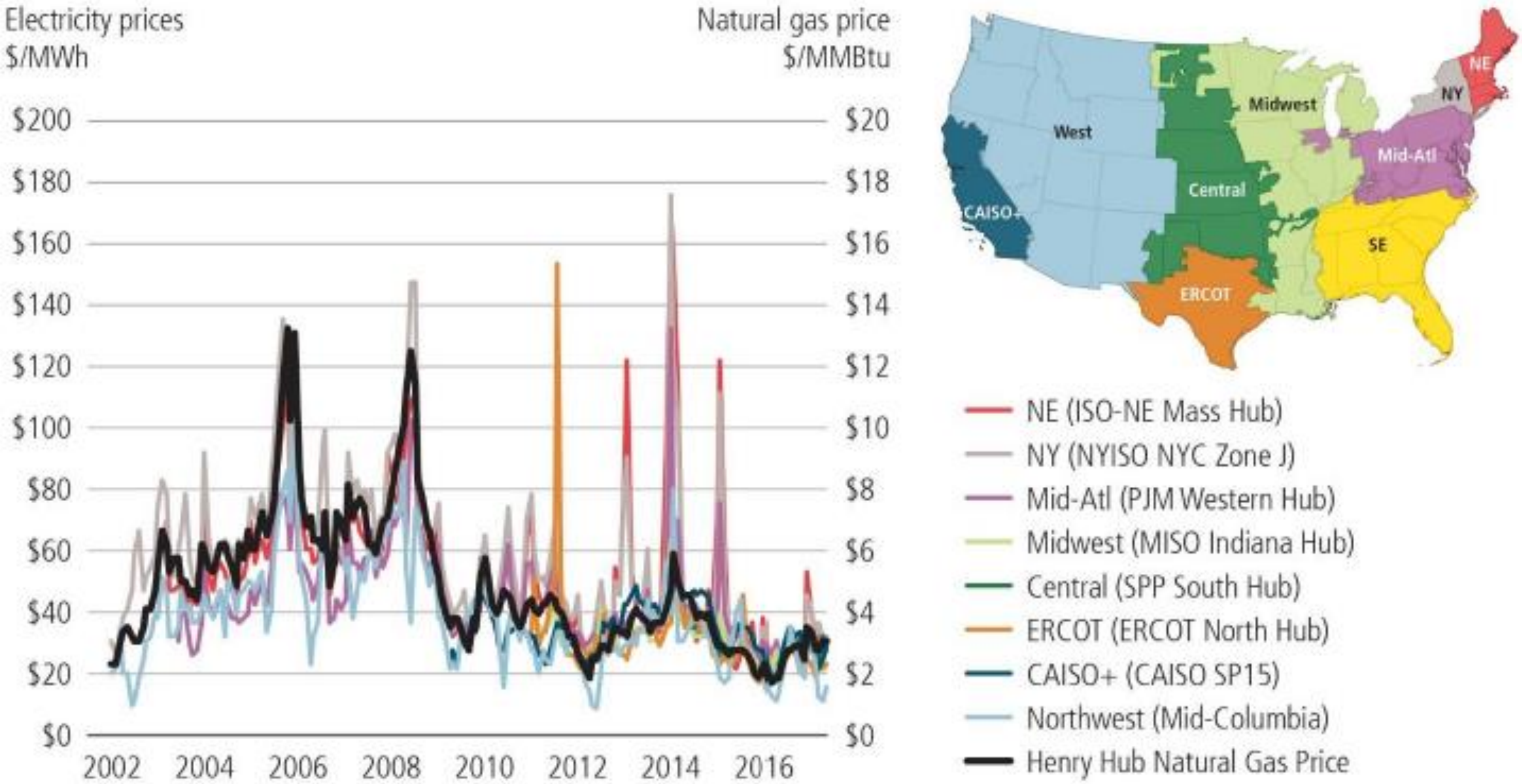
- Report requested by DOE Secretary
  - Electricity market evolution
  - Resource compensation and system resilience
  - Regulatory burdens; premature retirements of baseload plants
- Main findings
  - Wholesale markets are functioning
  - System reliability is maintained
  - Higher need for system flexibility
  - Some attributes not compensated
    - <u>Resilience</u>, jobs, pollution
  - Electricity markets must evolve
    - Price formation
  - Base load retirements
    - Mainly due to low natural gas prices

Staff Report to the Secretary on Electricity Markets and Reliability

August 2017

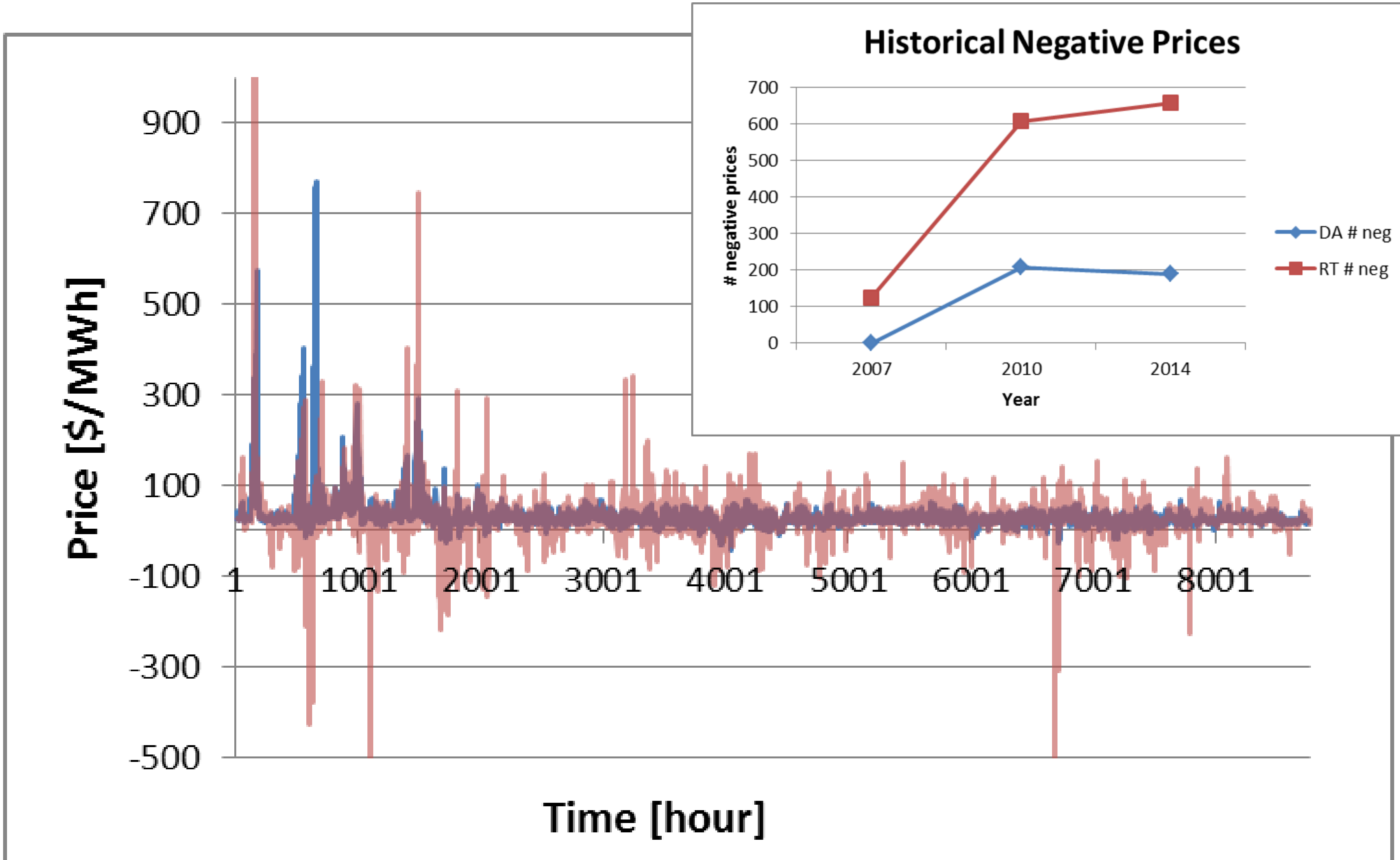
Electricity and Natural Gas Prices

Figure 3.18. Wholesale Day-Ahead Electricity Prices vs. Henry Hub Natural Gas Price (Monthly Average)[106]



U.S. DOE Staff Report (2017)

Wind Power and Electricity Market Prices



2014 Prices in Illinois PJM Node: 4 QUAD C18 KV QC-1

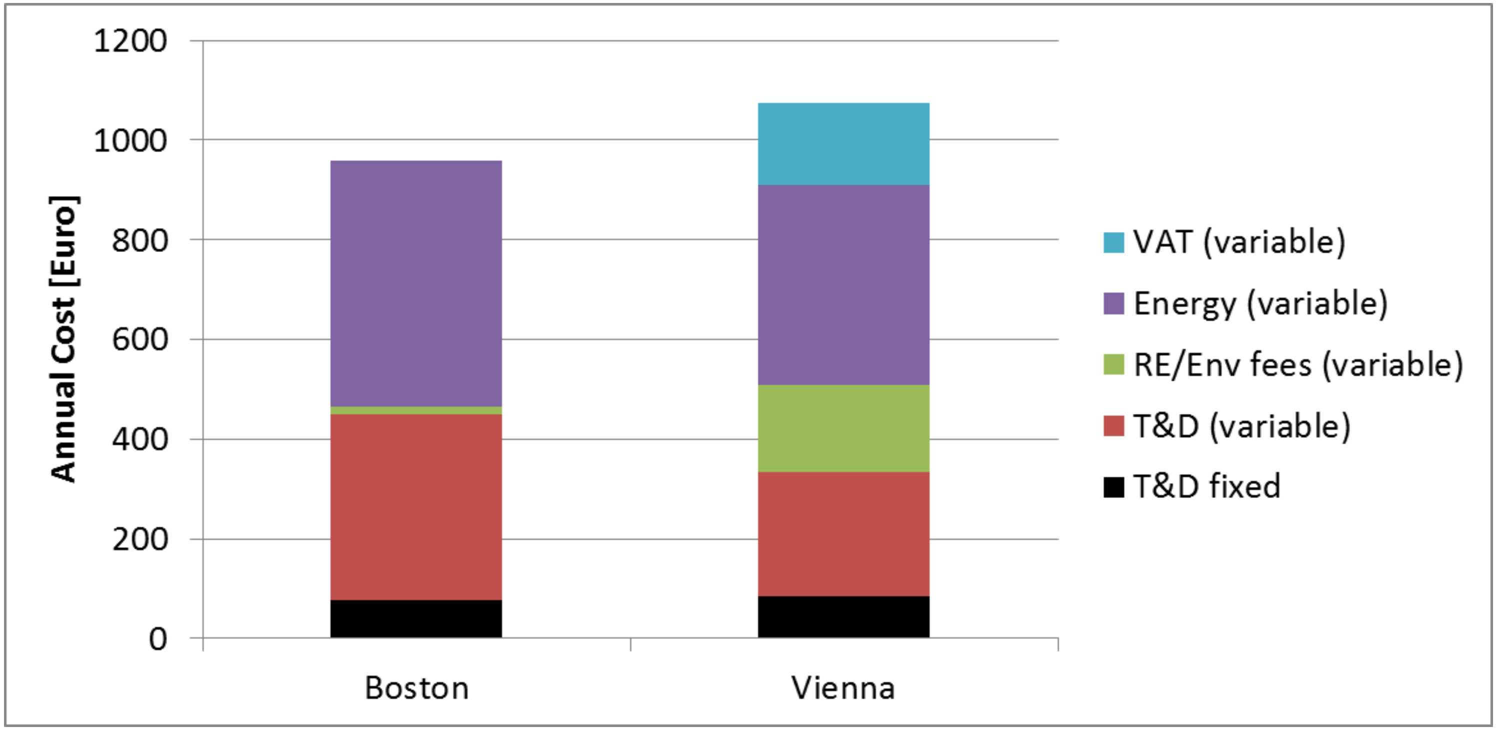
Electricity Market Design – US vs Europe

- **United States**
  - Build into existing system operators (ISOs)
    - Emphasize physics of the power system
    - Short-term system operation
    - ISOs do not own transmission system
  - Short-term market operations
    - Day-ahead market (ISO - hourly)
    - Real-time market (ISO - 5 min)
    - Complex bids/ISO UC
    - Locational marginal prices
    - Co-optimization of energy and reserves
  - Variable Renewable Energy (VER)
    - Tax credits, renewable portfolio standards
    - “Dispatchable” VER
  - Resource Adequacy
    - Energy only markets
    - Capacity markets/obligations
    - Integrated resource planning

- **Europe**
  - Introduced new power exchanges (PXs)
    - Emphasize markets and economics
    - Includes long-term contracts
    - TSOs typically own transmission system
  - Short-term market operations
    - Day-ahead and intraday markets (PX)
    - Real-time balancing (TSO)
    - Simple bids/generator UC
    - Zonal pricing/market coupling
    - Sequential reserve and energy markets
  - Variable renewable energy (VER)
    - Feed-in tariffs, tenders/auctions
    - VER as “must-take”
  - Resource Adequacy
    - Energy only markets
    - Capacity payments/markets
    - Strategic reserves

Distributed Generation and End-Use Tariffs

- "Net metering" a very hotly debated topic
- Example: Residential customer bills in Boston and Vienna
  - Annual consumption: 5000 kWh



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  - Energy storage
  - Nuclear flexibility
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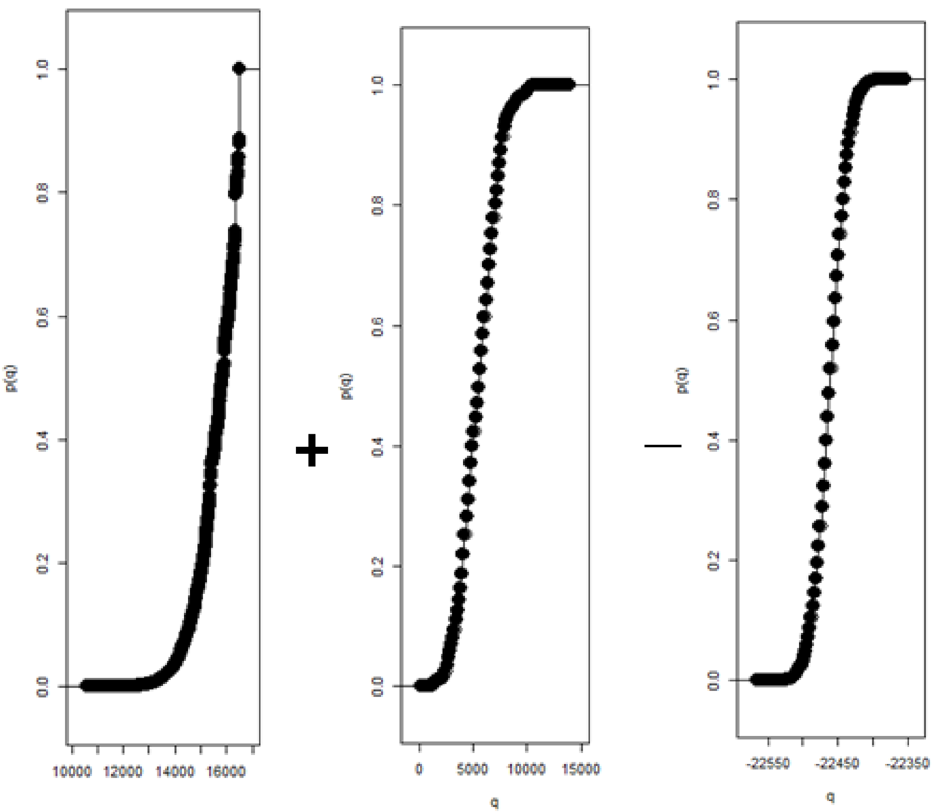
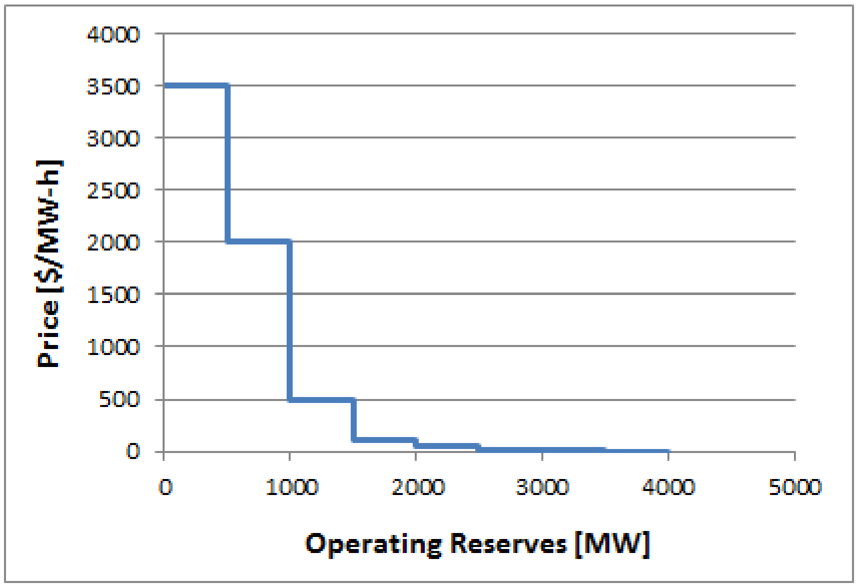
A Dynamic Operating Reserve Demand Curve (ORDC)

- Consider the uncertainties from load and supply
  - Probabilistic wind power forecast based on Kernel Density Estimation (Bessa et al. 2012)
- Estimate the risk of supply shortage for system
- Link the expected cost of this risk to the price to pay for reserves (Hogan 2005)

Thermal generators *Wind power* *Load*



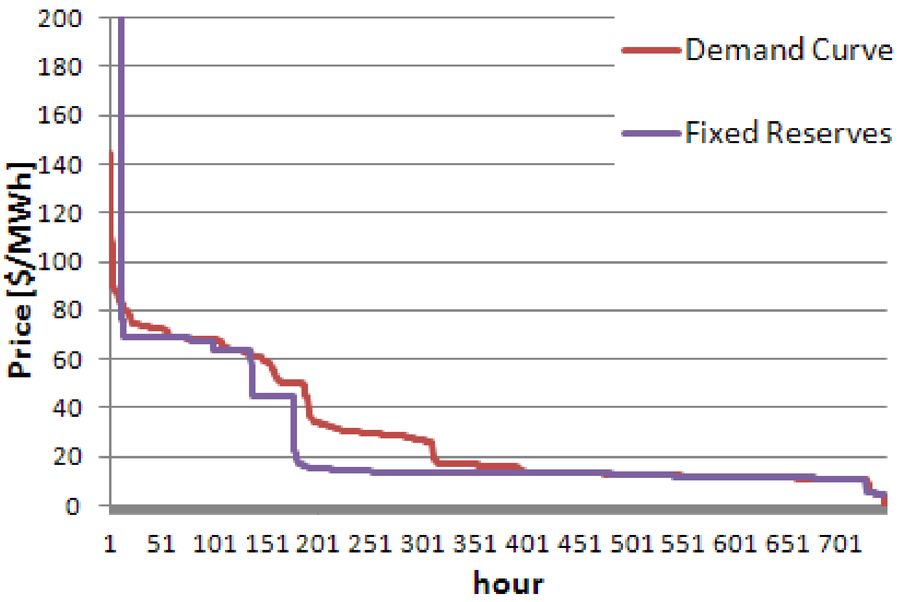
→ Loss of Load Probability x Value of Lost Load ↓



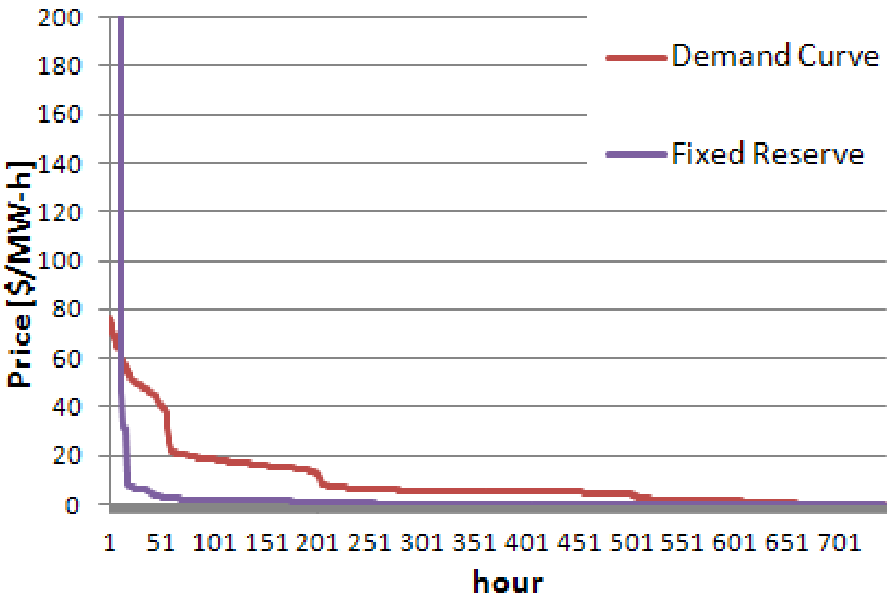
Benefits of Operating Reserve Demand Curves

- Results from simulation of co-optimized electricity market (Illinois case, 20% wind)

Energy price distribution (July)



Reserves price distribution (July)

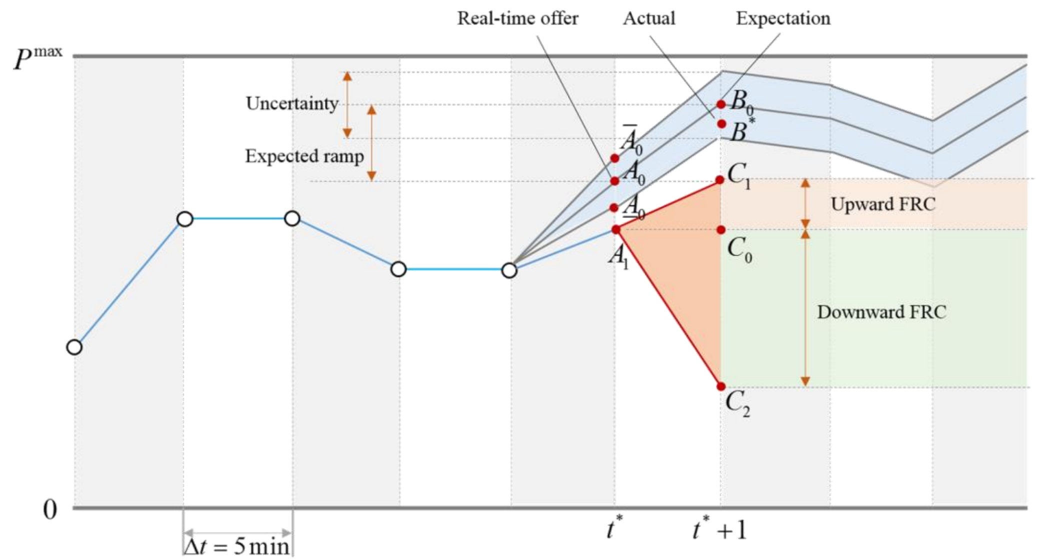


- Multiple benefits of a dynamic demand curve for operating reserves
  - Adds demand-side flexibility to system scheduling and dispatch
  - Better reflects wind power forecast uncertainty in prices
  - Gives higher prices for energy and reserves in most hours, fewer extreme price spikes
  - Stabilizes revenues for generators, addresses missing money (Levin and Botterud, 2015)
  - “Static” ORDCs implemented in ERCOT/Texas market in 2014, considered in Belgium

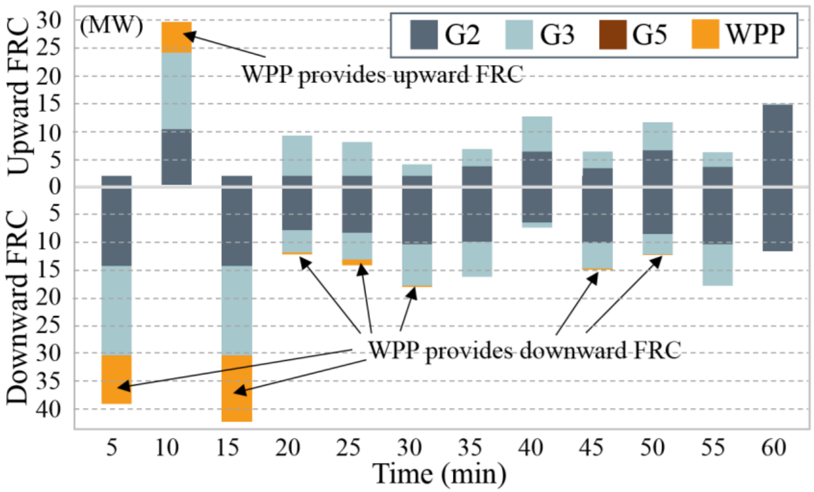
Zhou and Botterud. IEEE Trans. Power Systems, 29(1): 160-171, 2014.

Wind Power Providing Flexi-Ramp Capacity (FRC)

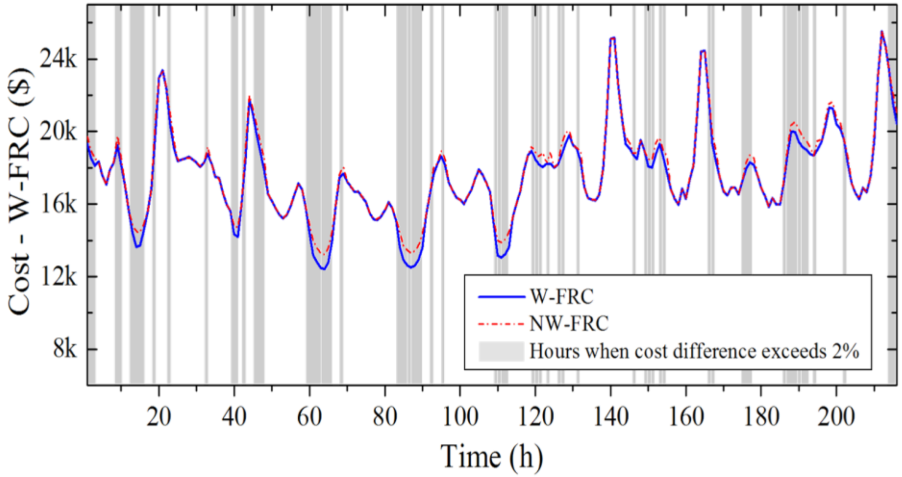
- Wind turbines are capable adjusting their active power output at the rate of 0.05-0.25 p.u./s.
- By operating below available capacity, the wind power producers (WPPs) are capable of offering ramping service.
- Though the WPPs' opportunity cost of providing FRC is high, it is economic if frequent commitment of fast-start unit can be avoided.



WPP providing FRC: G5 is not committed



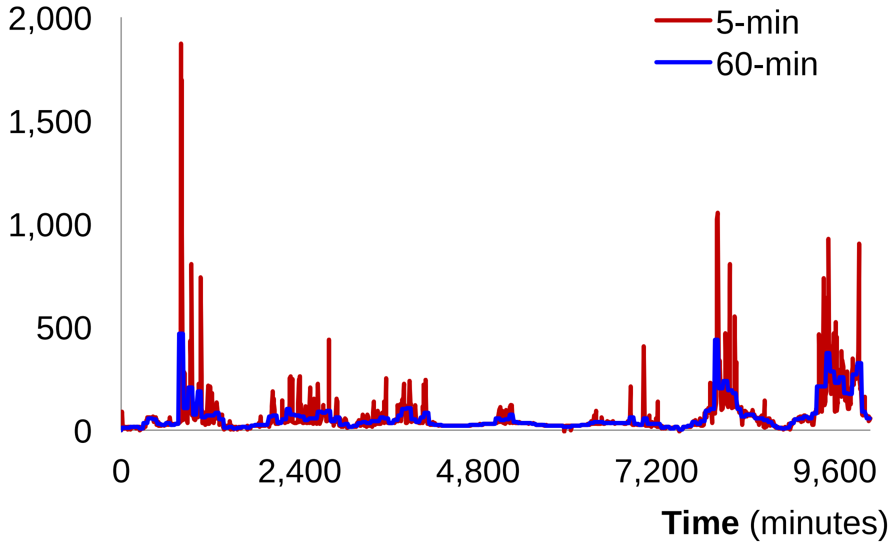
System cost is reduced for most of the cases



Chen et al., IEEE Trans. Power Systems, 32(3): 2049-2061, 2017.

Price Resolution and Energy Storage Arbitrage

Real-time price (from a MISO node)
$/MWh



Battery models – Increasing technical resolution

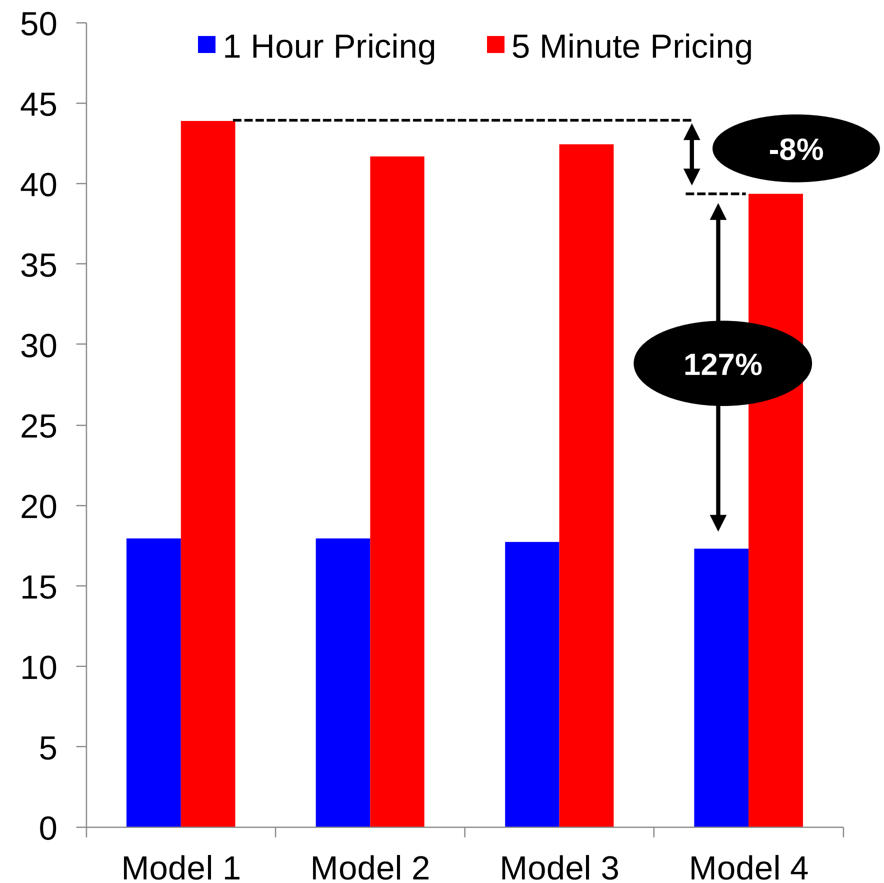
Model 1: Fixed power limits, fixed efficiency.

Model 2: SOC dependent power limits, fixed efficiency.

Model 3: Fixed power limits, efficiency as a function of power.

Model 4: SOC dependent power limits, efficiency as a function of power and SOC.

Net revenue for 10MWh Li-ion storage system
$k/week

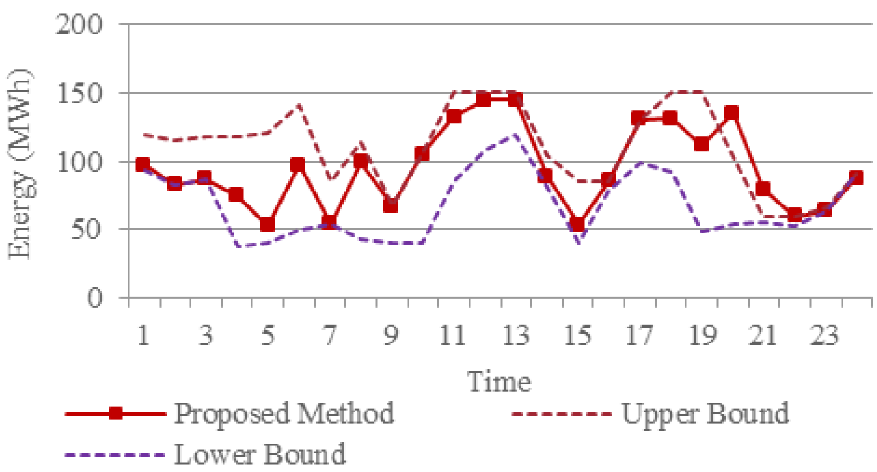


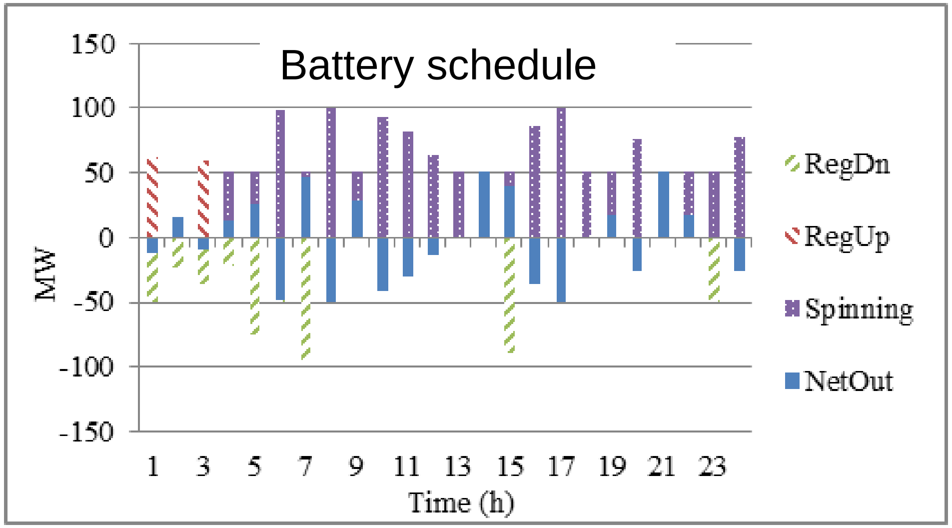
Moving from hourly to 5-min price resolution more than doubles energy arbitrage revenue (required by FERC order 825)

Sakti et al., J. Power Sources, 342: 279-291, 2017.

Short-term System Benefits of Energy Storage

- A stochastic day-ahead unit commitment model with energy storage and wind power
  - IEEE RTS system: 2656 MW load, 15%-30% wind power (345-690 MW)
  - Battery: 50MW/150MWh (3 hours), 10% loss in each direction





Average day-ahead cost savings from battery:

Wind %	Total Cost with Battery ($)	Total Cost without Battery ($)	Cost Savings ($)	Cost Savings (%)
15%	806,287	930,440	124,154	13.3%
20%	765,307	887,480	122,173	13.8%
25%	733,779	849,963	116,184	13.7%
30%	712,808	827,570	114,762	13.9%

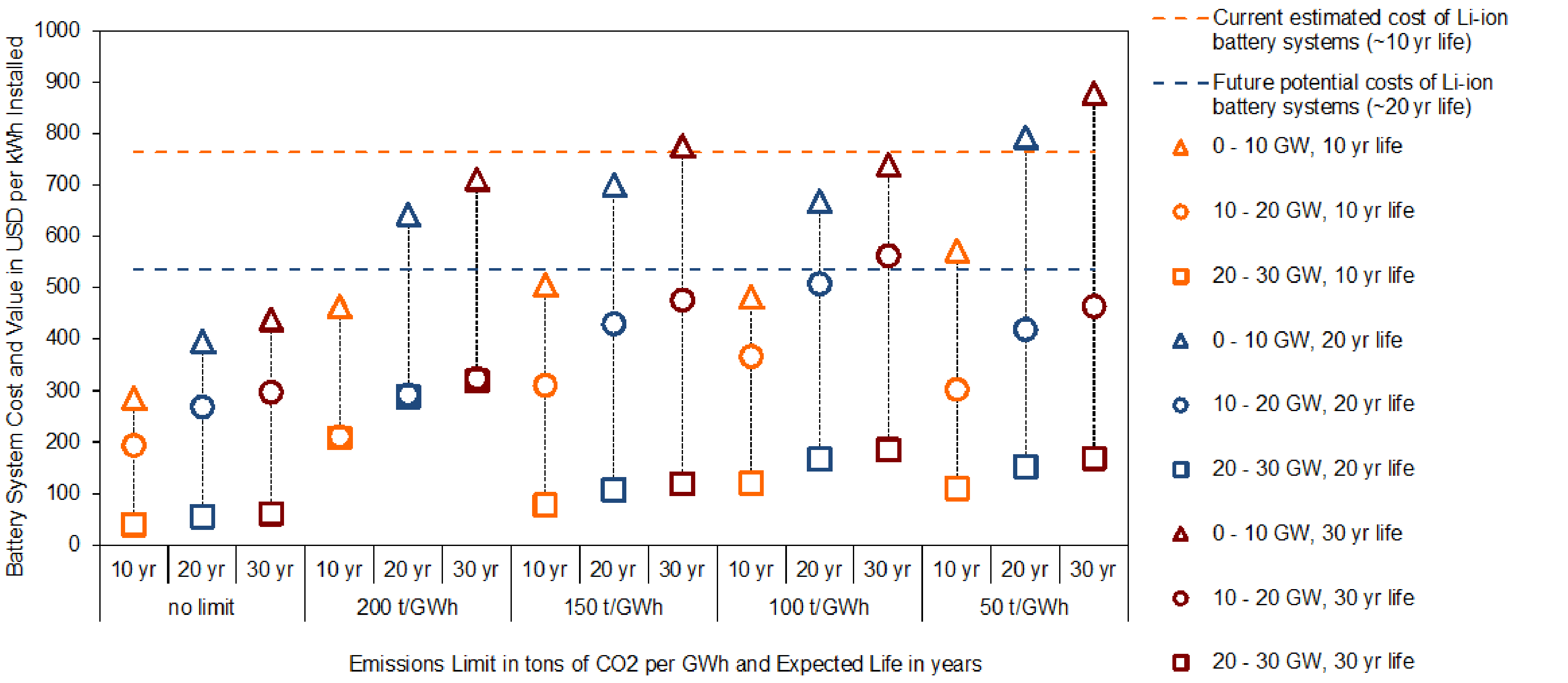
NPV of cost savings from battery at 25% wind: $1200/kWh-capacity
(@5500 cycles/5 year lifetime, 8% interest)

Note: small, high cost system.

What is the Value of Energy Storage to the Future Grid?

- Optimal generation expansion with emissions targets (IMRES model)
  - Wind, solar, and load data for ERCOT/Texas for 2035, greenfield expansion
  - Increasingly stringent emissions targets (today 600 tCO_2/GWh)
  - Different energy storage levels (2 hr storage, 20% roundtrip losses, 10% interest)

Estimated benefits (avoided generation costs) and costs of energy storage



de Sisternes, Jenkins, Botterud, Applied Energy, 175: 368-379, 2016.

Nuclear Power as a Flexible Resource

- More interest in nuclear flexibility with increasing renewable penetration levels
  - United States: Nuclear energy is currently baseload
  - Europe: Flexible nuclear operations (e.g. France, Germany)
- Unique operational constraints of nuclear power
  - After ramp-down, must wait to ramp back up (xenon poisoning)
  - Function of power history, time in fuel cycle
- Simulating impacts of nuclear flexibility (representative data from Southwest U.S. w/22% solar/wind, 25% nuclear)
  - 1.3-1.6% reduction system operating cost
  - 2.0-4.7% increase in nuclear gross operating margin
  - 43-58% reduction curtailment of renewables

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Concluding Remarks

- Electricity markets and renewable energy
  - Fundamental challenges: uncertainty, variability, low marginal cost
  - U.S. electricity markets stood the test so far, but there are challenges ahead
- Solutions to renewable integration challenges
  - Supply flexibility, demand response, energy storage
  - Forecasting, operational practices, market design
  - Most cost effective solutions should prevail
  - Lessons can be learned from Europe and U.S.
    - Intraday markets, long-term markets (Europe -> United States)
    - Co-optimization energy and reserves, locational high-frequency pricing, dispatchable renewables (United States -> Europe)

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  - Argonne National Laboratory

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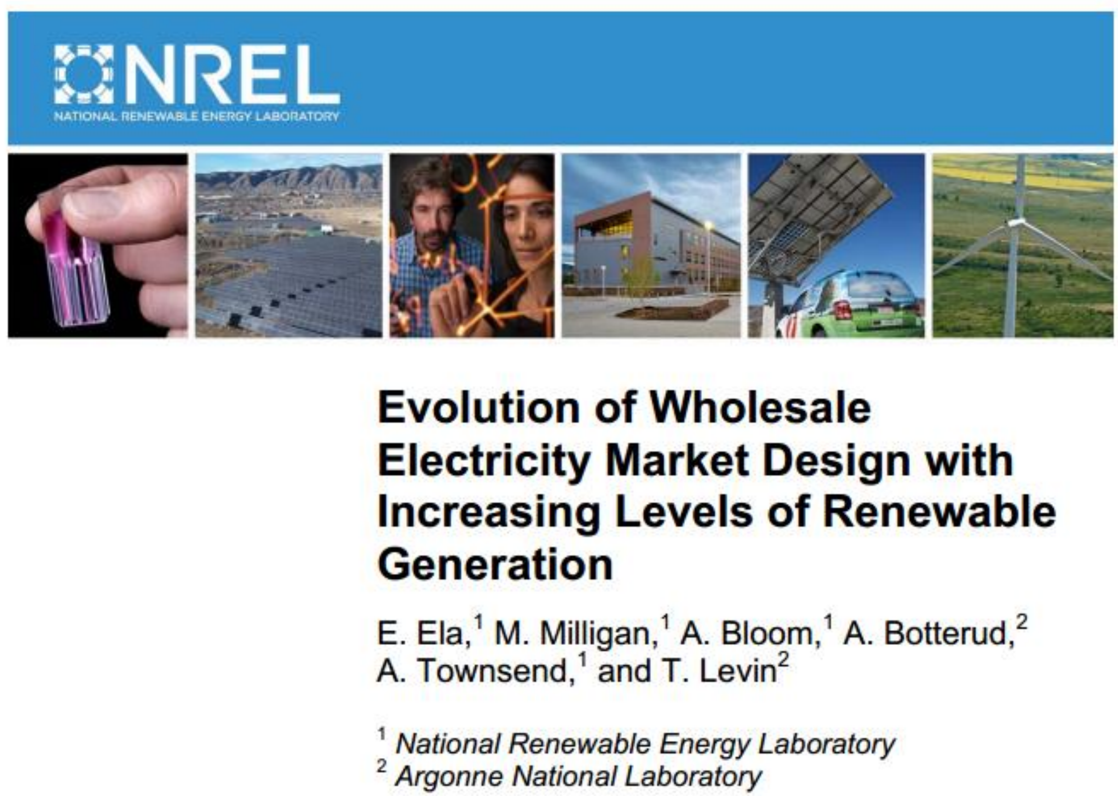
Electricity Markets and Reliability

- In April 2017, the DOE Secretary requested a report to explore three issues
- Market Evolution
  - Are energy and capacity markets adequately compensating attributes that strengthen grid resilience (e.g. on-site fuel supply)?
  - If not, how might this affect grid reliability and resilience in the future?
- Resource Compensation and System Resilience
  - How are policy interventions and changing resource mixes impacting the original policy assumptions that shaped the creation of current electricity markets?
- Regulatory Burdens
  - Have regulatory burdens, mandates, taxes and subsidies, led to the premature retirement of baseload power plants?

Electricity Market Design with Renewables

- Review of current and proposed market designs
  - How to achieve capacity adequacy and revenue sufficiency in the long-run?
  - How to ensure and incentivize flexibility in short-run operations?


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation

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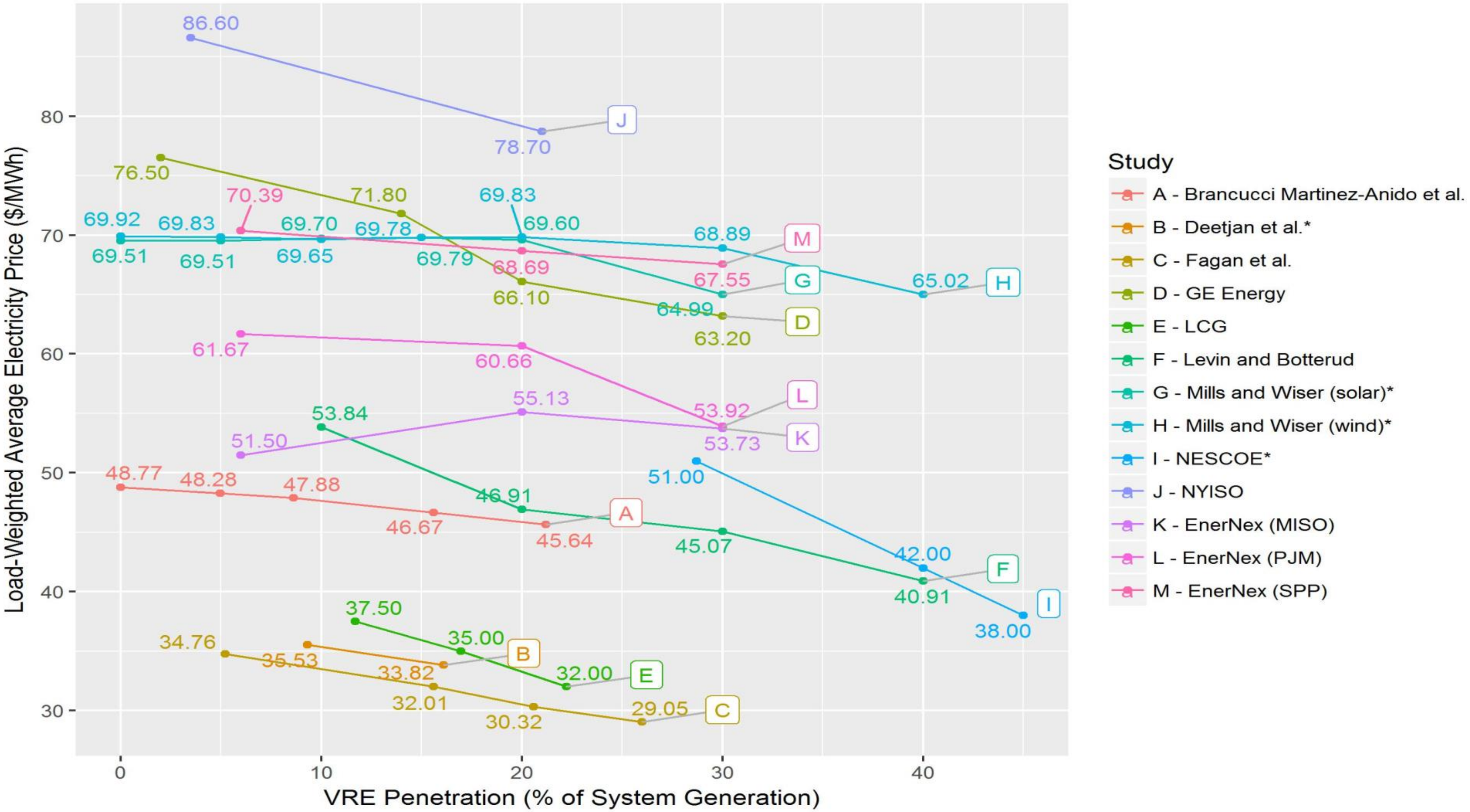
[1] *National Renewable Energy Laboratory*
[2] *Argonne National Laboratory*

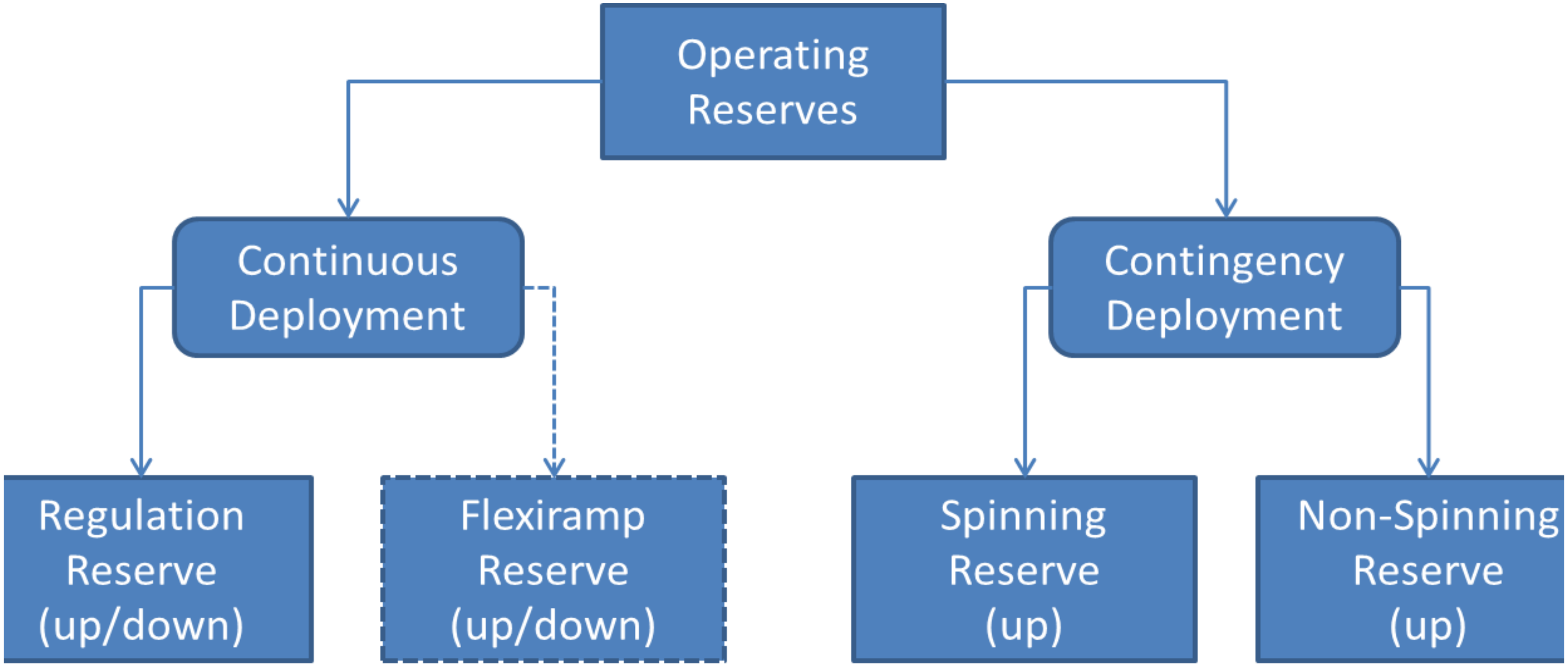
Technical Report NREL/TP-5D00-61765, Sept. 2014.

Prediction of Future Price Impacts of Renewables



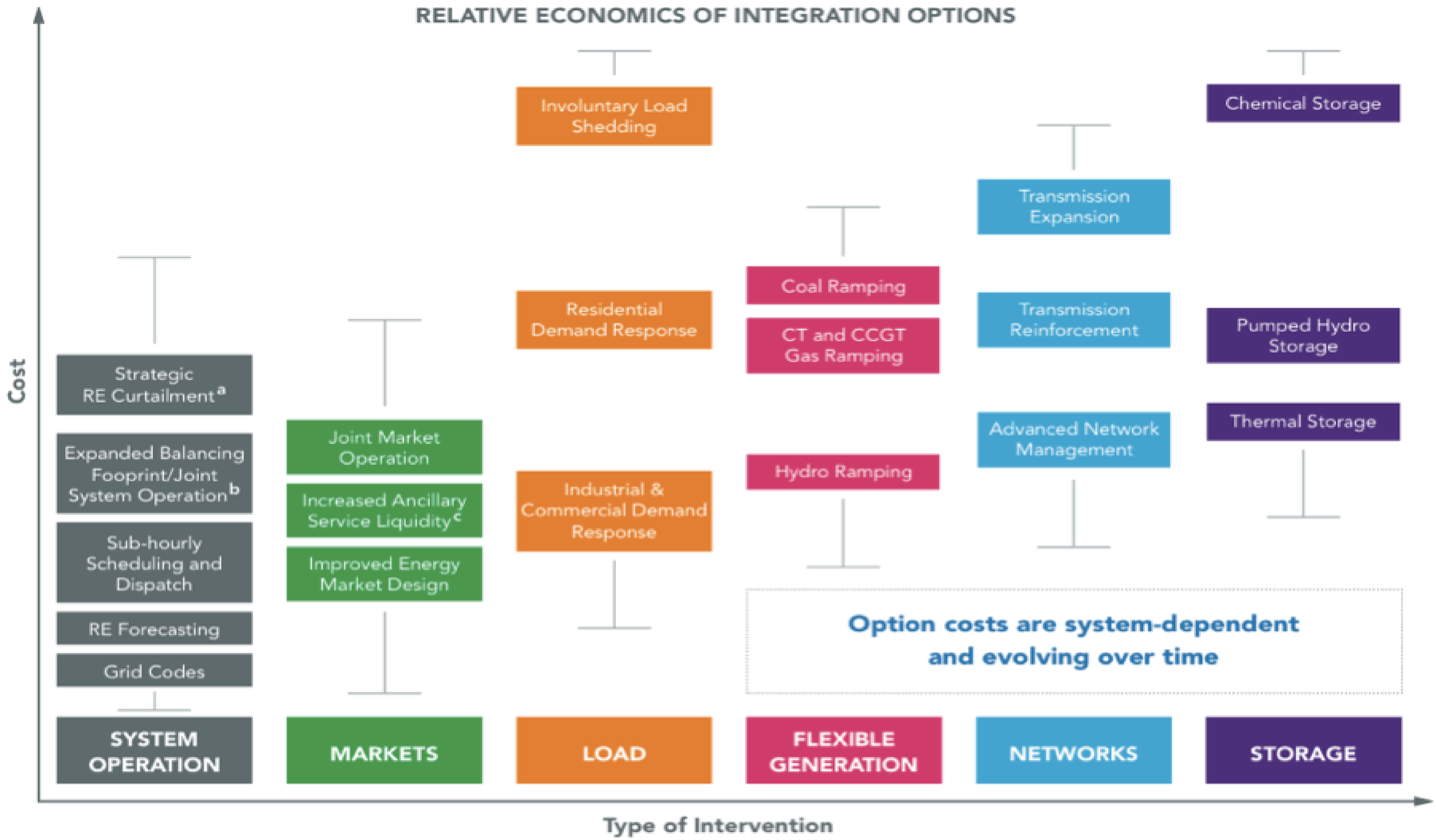
Most studies predict lower prices with more renewables

Evolving Markets for Operating Reserves



- Regulation reserve: Pay for performance
- More dynamic assessment of reserve requirements
- “Flexi-ramp reserves” to ensure sufficient ramping capability available in real-time
  - California ISO (CAISO)
  - Midcontinent ISO (MISO)

Many Solutions for Integrating Renewables



Cochran et al., NREL/TP-6A20-61721, 2014

ORDC and system expansion?

- Quote from recent capacity adequacy study