# Electricity Markets and Renewable Energy: United States vs. Europe


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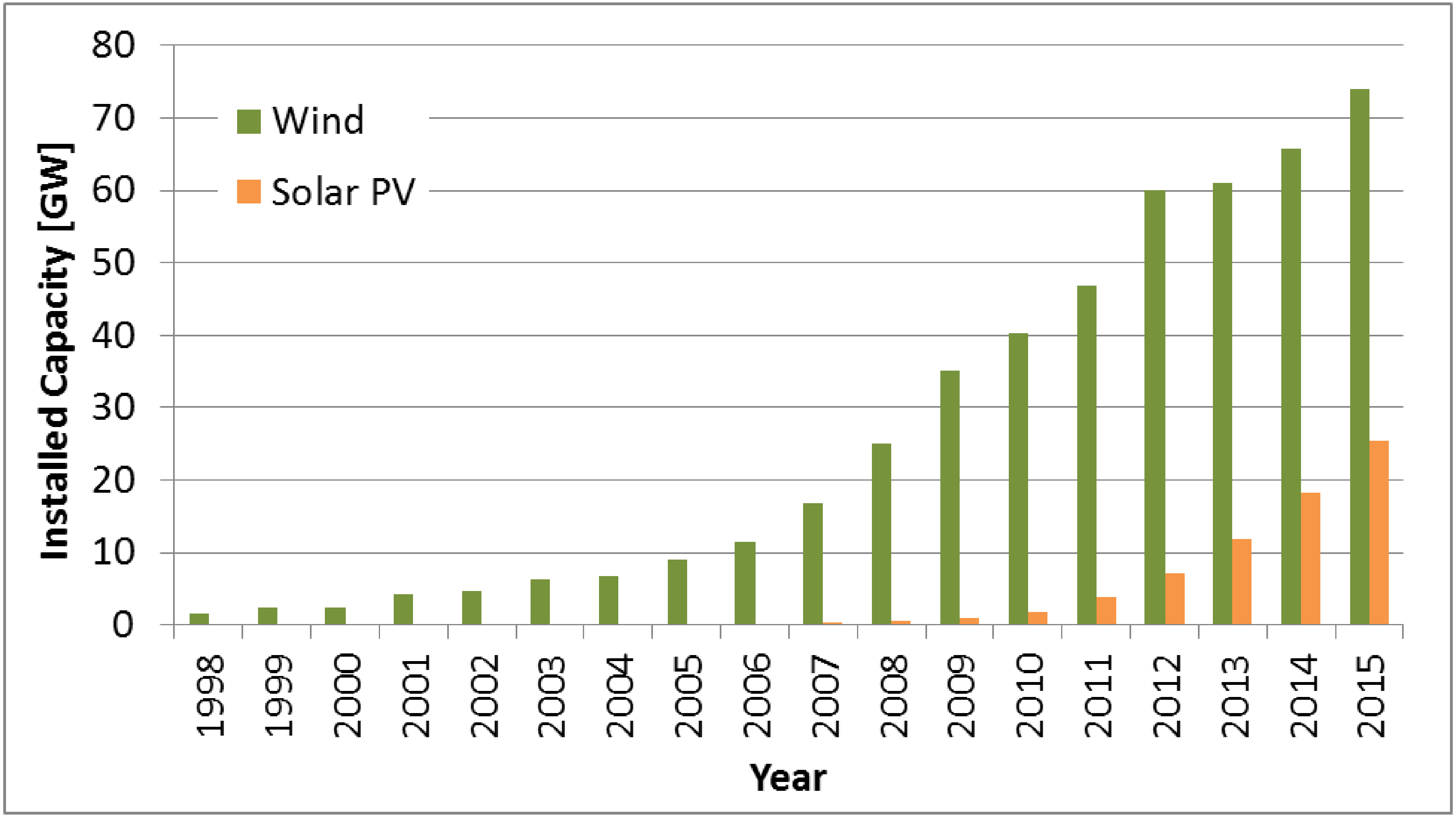
# *Outline*

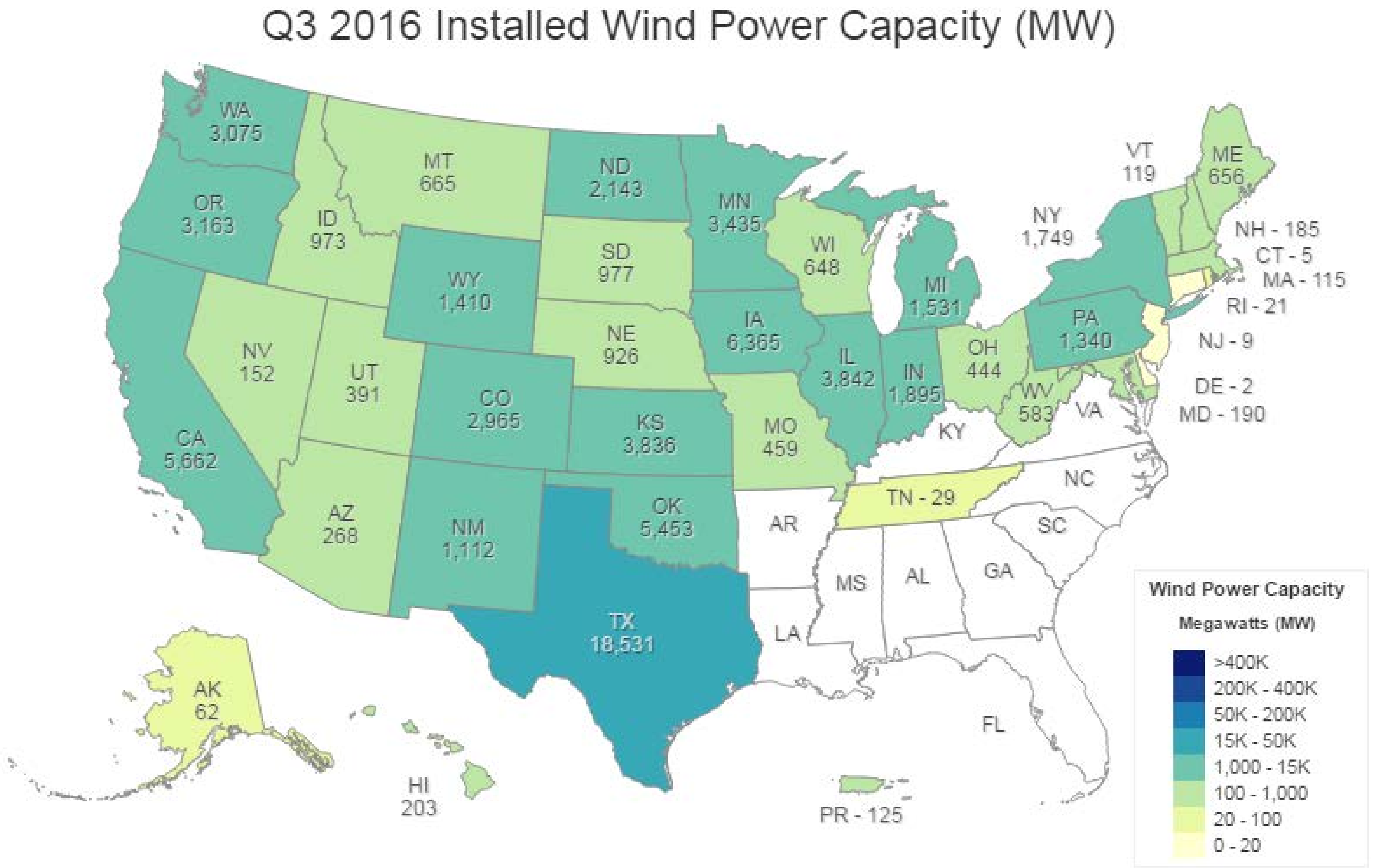
- Background
  - Renewable energy penetration levels
  - Electricity market operations
  - Core research questions
- Addressing Renewables in Short-term Operations
  - Operating reserve demand curves
- Addressing Renewables in Long-term Planning
  - Generation Expansion and Revenue Sufficiency
- Concluding Remarks

# Rapid Growth in U.S. Renewable Energy Capacity




**2015: Wind/solar meet 5%/1% of U.S. electricity load**

# Wind Power Capacity in the United States




Total Installed Wind Capacity: 75,714 MW

Source: American Wind Energy Association Q3 2016 Market Report

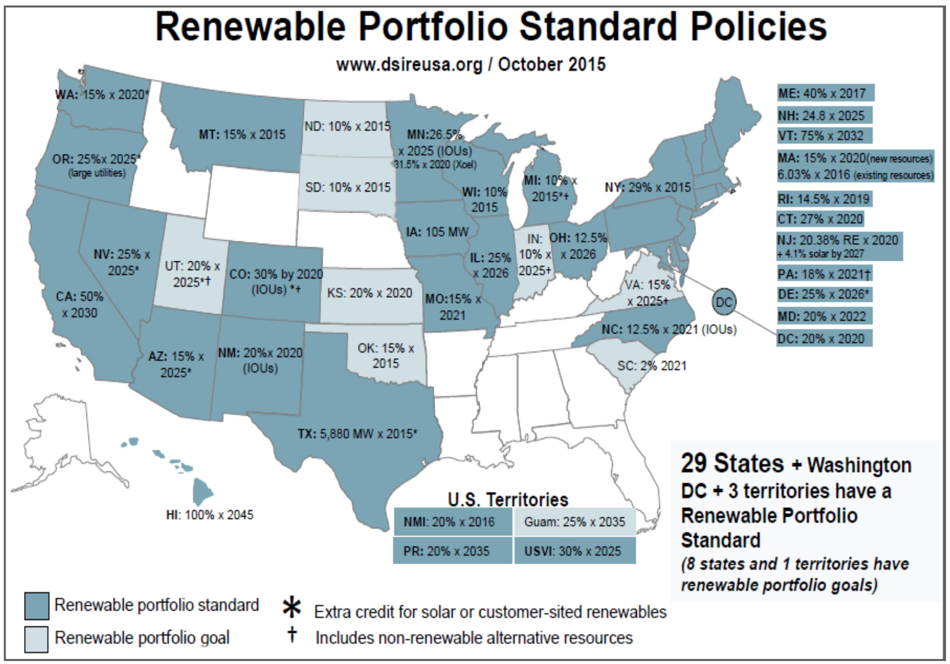
# Subsidy Schemes for Renewables

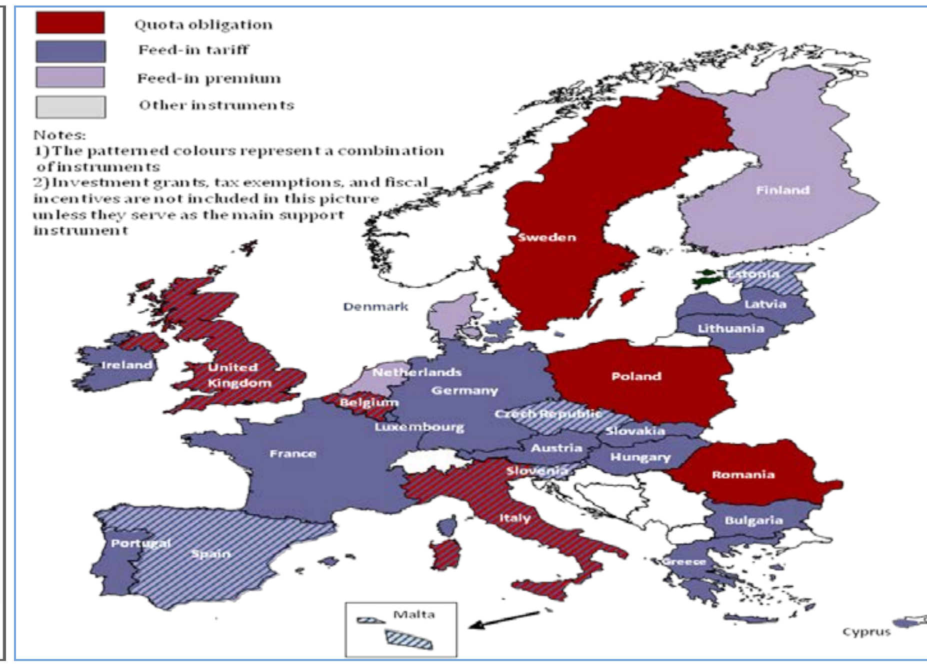
## United States (13.5% renewables in 2014)

- Direct support for renewables
  - Production/Investment tax credits (Federal)
  - Renewable portfolio standards/goals (State)
- Climate change policies
  - EPA's Clean Power Plan (stayed by Supreme Court)
  - Regional cap and trade programs

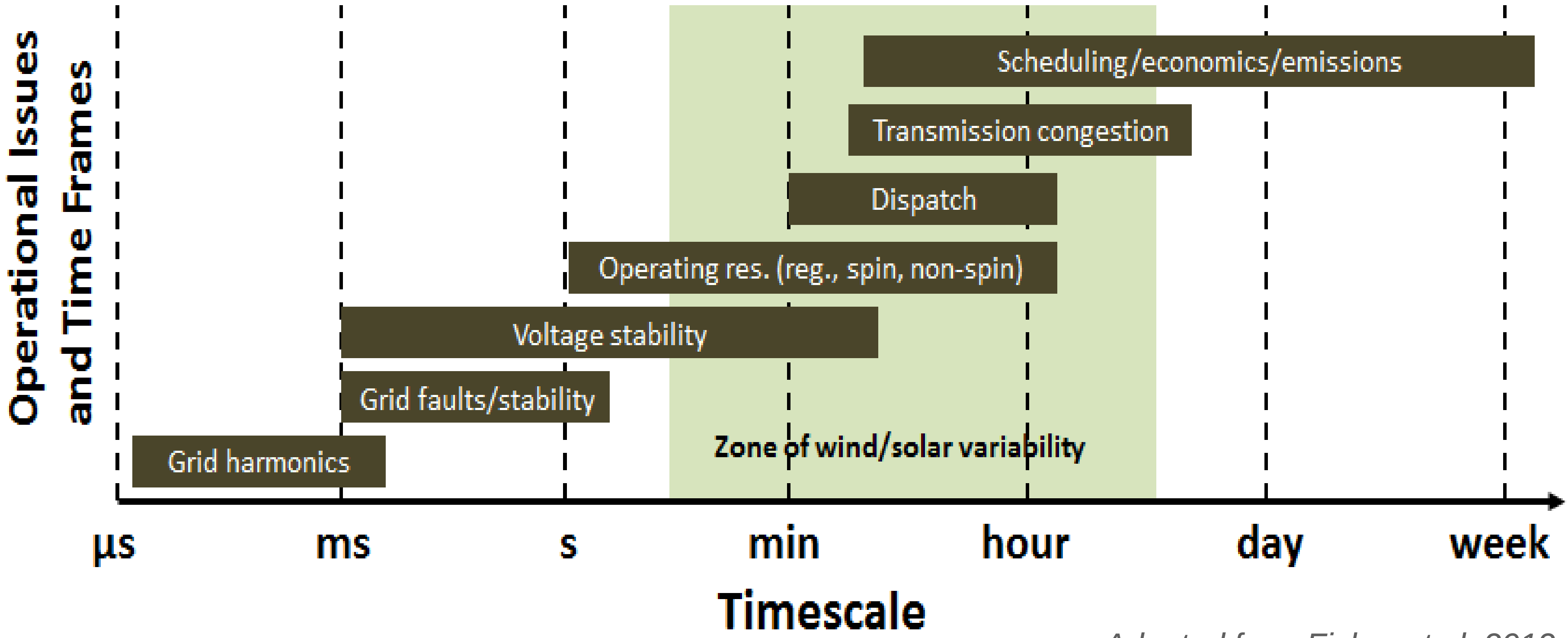
## Europe (27% renewables in 2014)

- Direct support for renewables
  - Feed-in tariffs for wind and solar
    - Fixed to premium tariffs and auctions
  - Green certificates
- Climate change policies
  - European Emissions Trading System (ETS)



# *Operating the Power Grid is Complex*




*Adapted from Fisher et al. 2012*

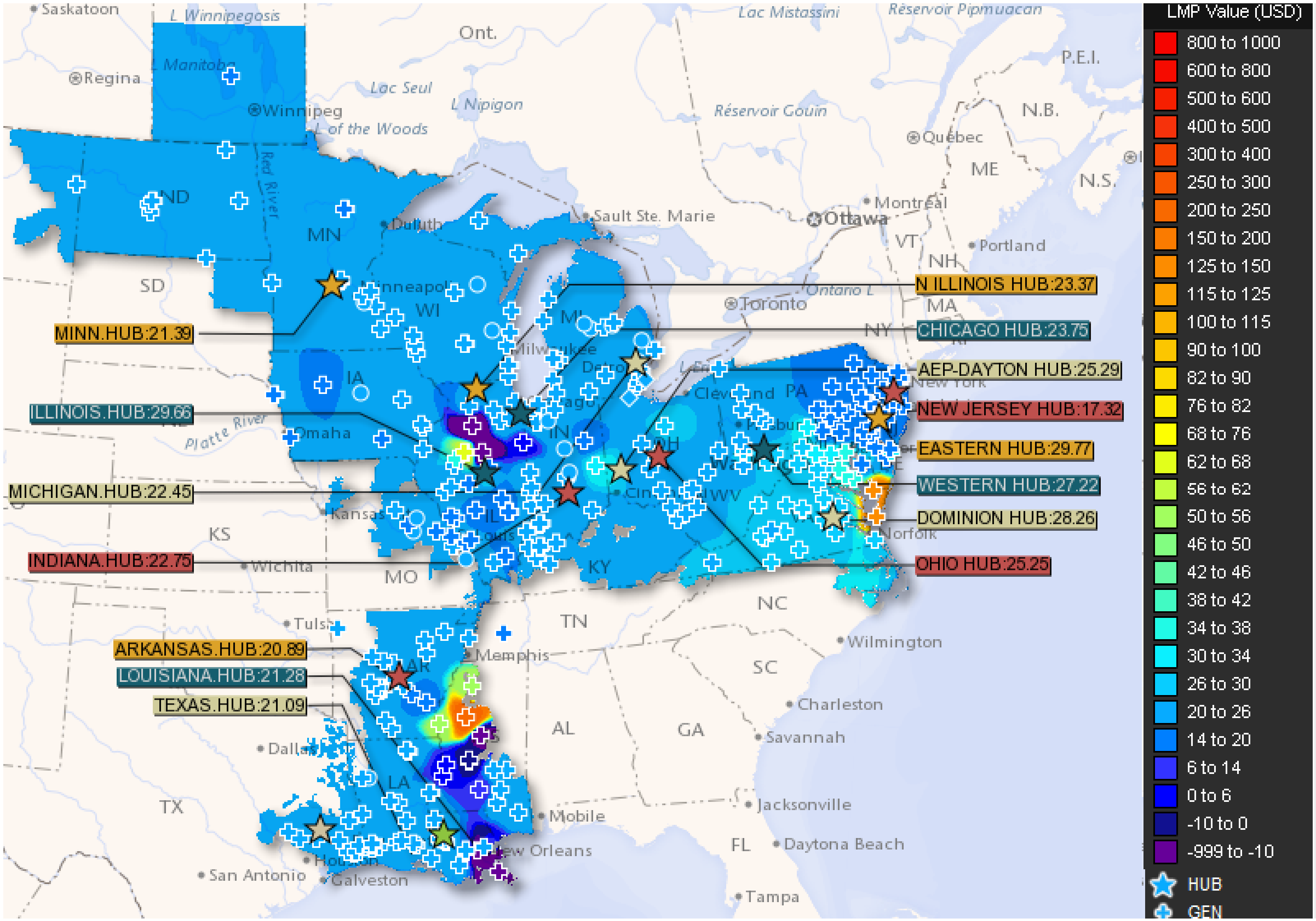
***Handling uncertainty in a cost-effective manner is at the core of the problem.***

# The General Structure of Electricity Markets

- United States
  - Build into existing system operators (ISOs)
    - Emphasize physics of the power system
    - Short-term system operation
    - ISOs do not own transmission system
  - Market design elements (United States)
    - 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)
    - “Dispatchable” VER

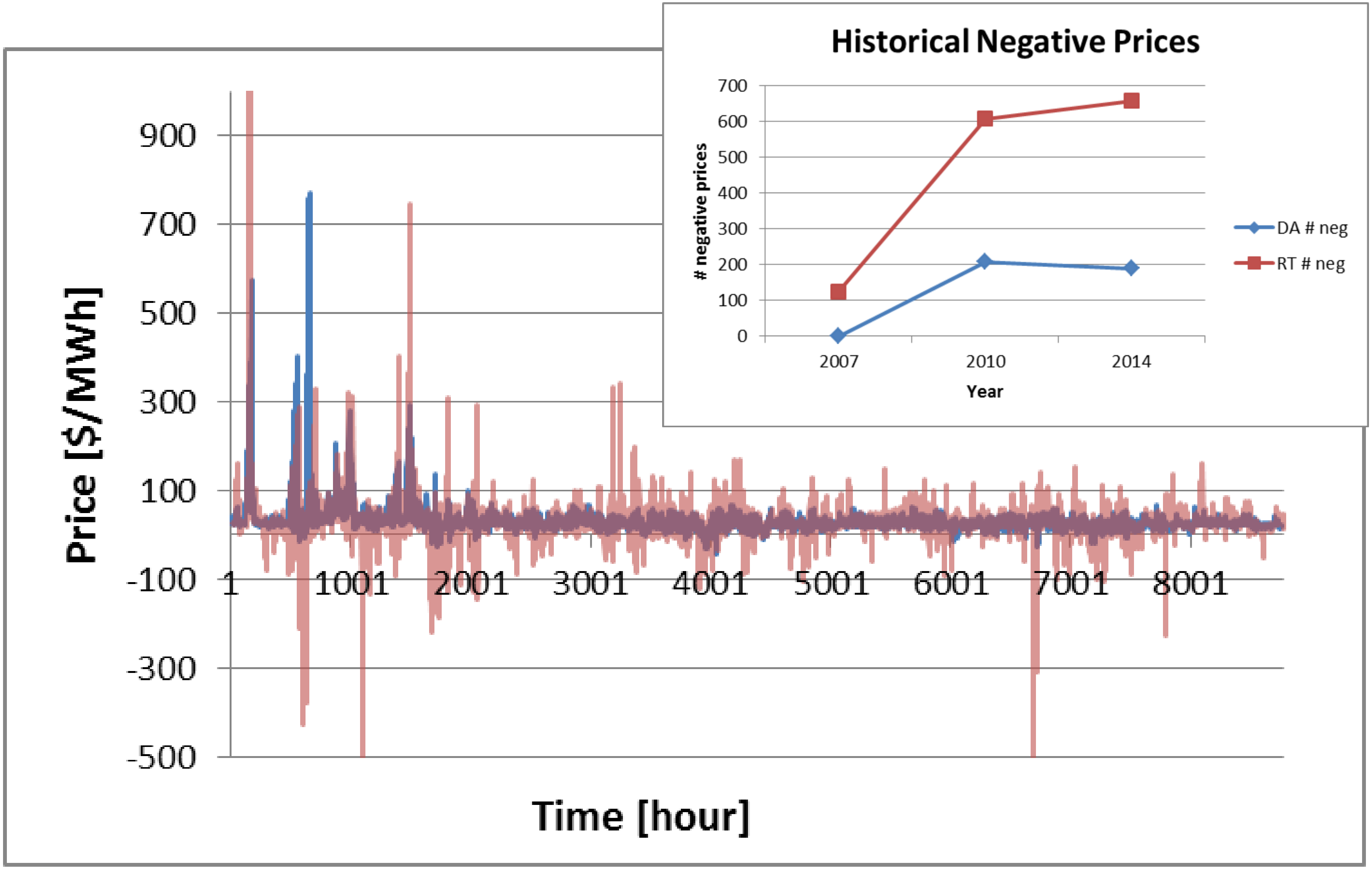
- Europe
  - Introduced new power exchanges (PXs)
    - Emphasize markets and economics
    - Includes long-term contracts
    - TSOs typically own transmission system
  - Market design elements (Europe)
    - Day-ahead market (PX)
    - Real-time balancing (TSO)
    - Simple bids/generator UC
    - Zonal pricing/market coupling
    - Sequential reserve and energy markets
  - Variable renewable energy (VER)
    - VER as “must-take”

# Congestion Management and Locational Marginal Prices (US)



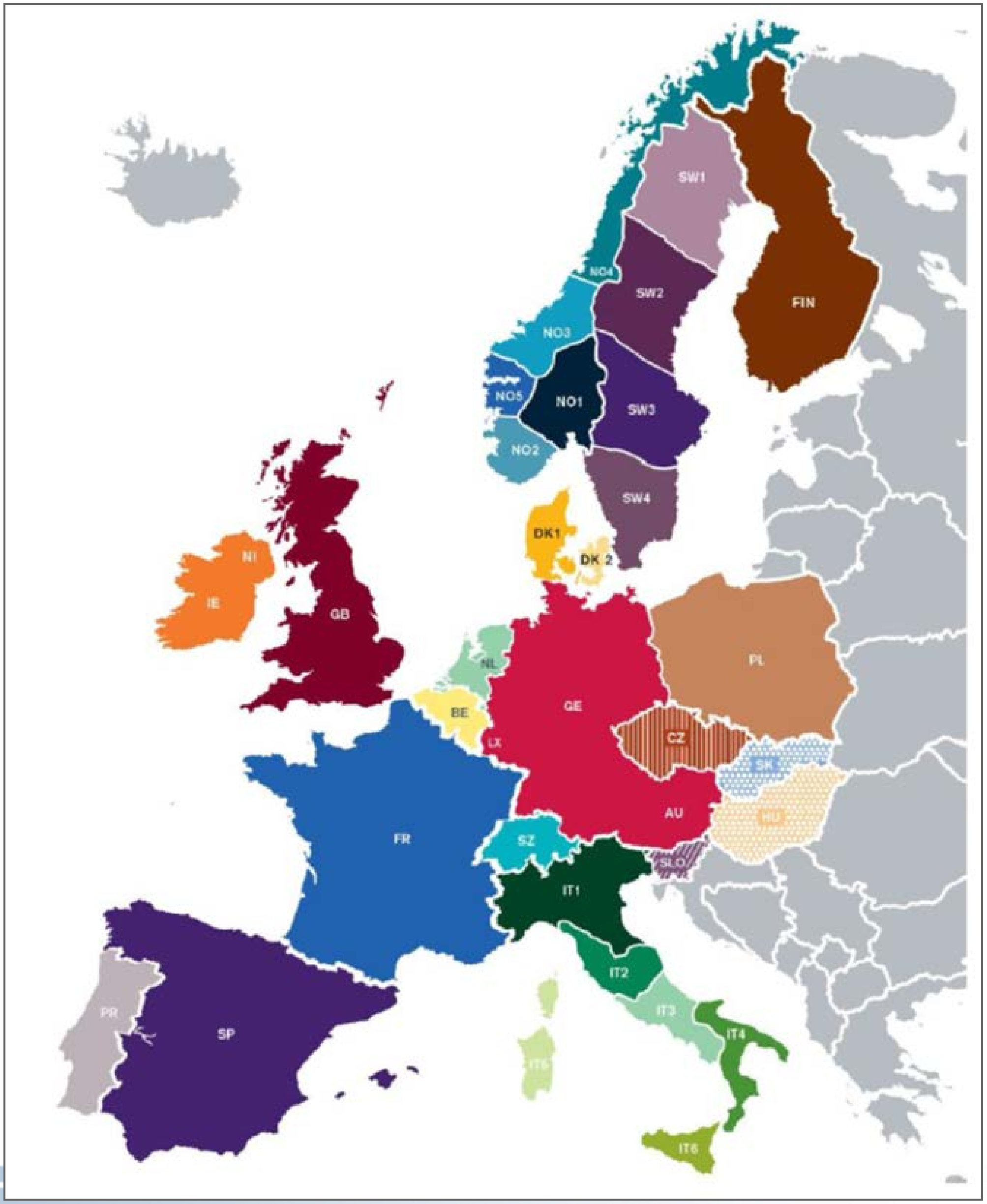

Nov 18 2015, 8.30am

# Wind Power Influences Electricity Prices Today: Day-ahead and Real-time Prices at Node in Illinois (2014)



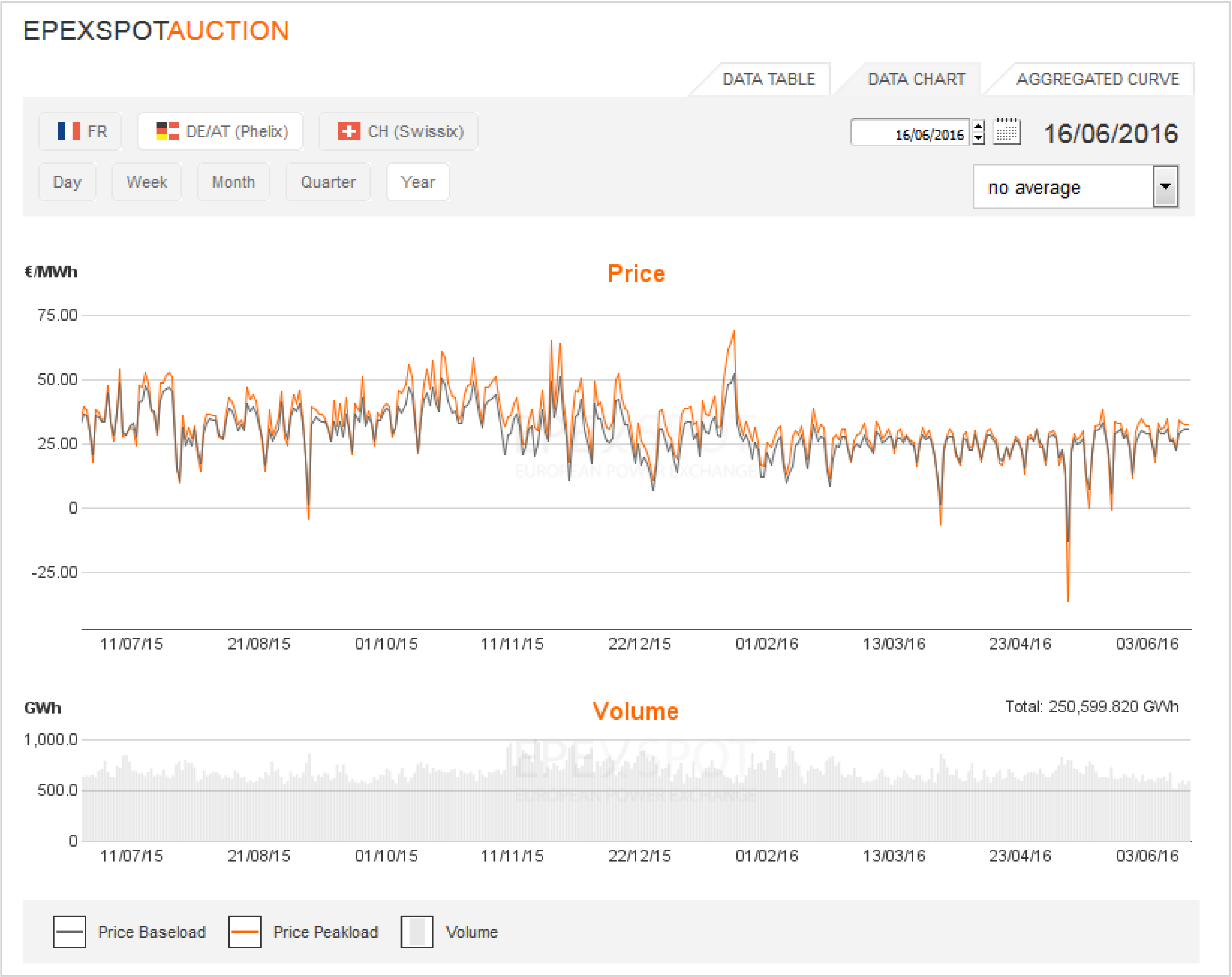

*Prices in Illinois PJM Node: 4 QUAD C18 KV QC-1*

# Price Zones in European Day-Ahead Markets




Courtesy: Hans Auer, TU Wien

# Electricity Prices in Central-Western Europe 2016

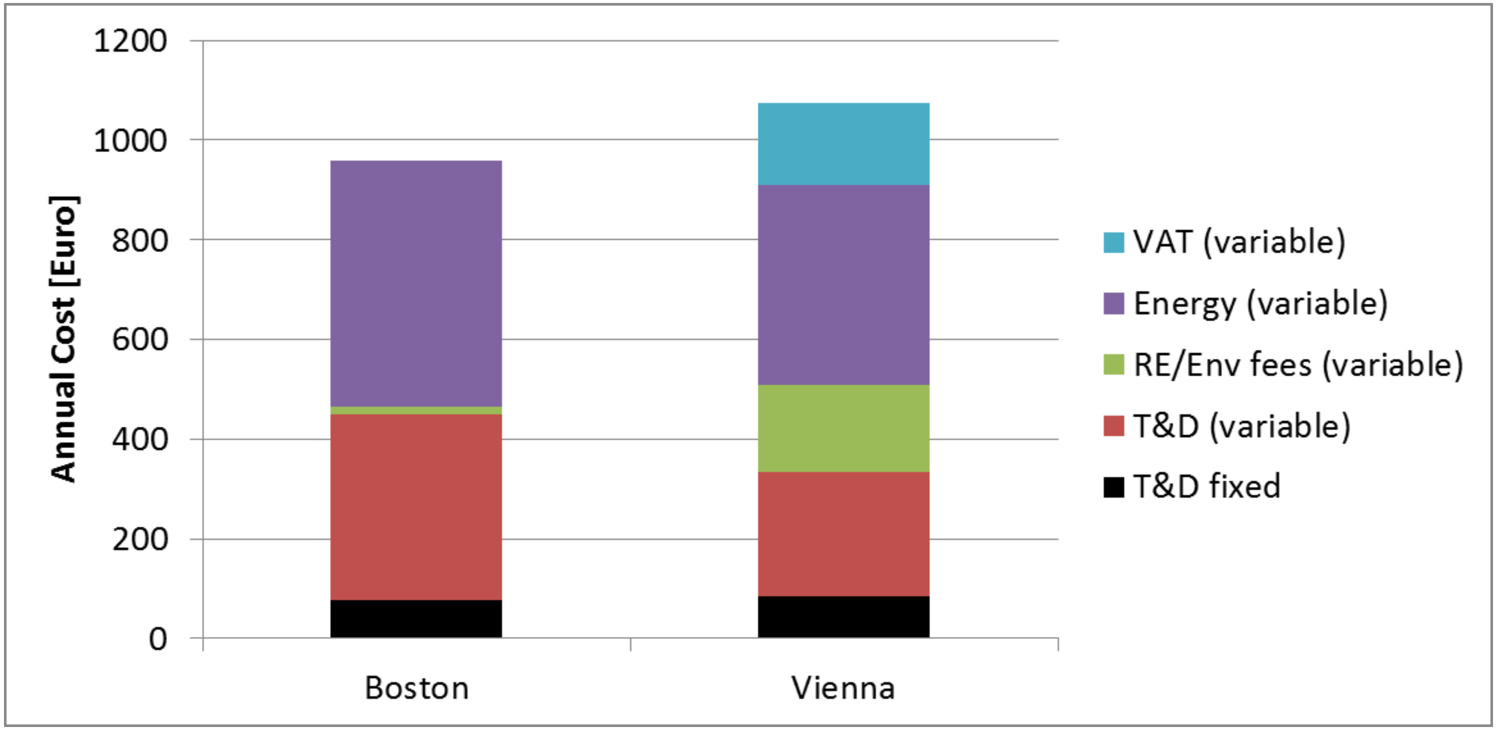



Central-Western Europe: EPEXSPOT (2016)

# Distributed Generation and End-User Tariffs

- “Net metering” a very hotly debated topic

- Example: Residential customer bills in Boston and Vienna
  - Annual consumption: 5000 kWh

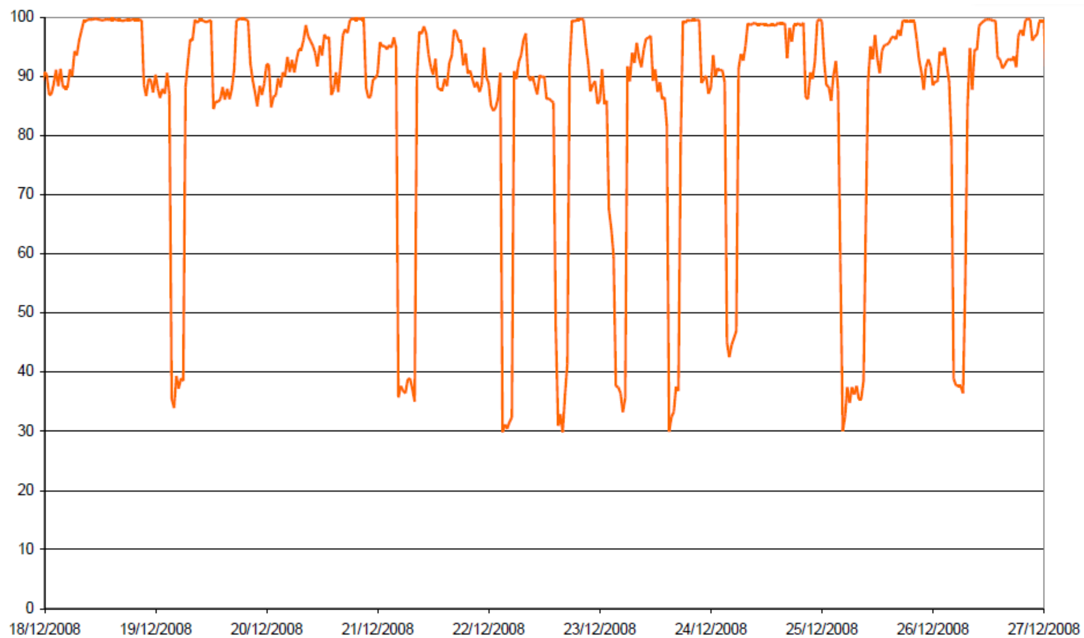


# Nuclear Power: A Source of Flexibility?

- Nuclear shut-downs
  - Primarily due to economics (US)
  - Public resistance (Europe)

- Importance of nuclear flexibility with increasing renewable penetration levels
  - United States: Nuclear energy is currently baseload
  - Europe: Flexible nuclear operations (e.g. France, Germany)

**Figure E.1: Example of a typical power history during a cycle in a EDF reactor (in % of the rated power)**




Courtesy of Électricité de France (EDF)

*Source: NEA, 2011*

# Core Research Questions

- How to plan and operate power systems with increasing shares of renewable generation?
- How to design electricity markets to provide adequate incentives for market participants?
- How to facilitate the transition to low-carbon power and energy systems?
- Develop improved analytics for evolving electricity markets and energy systems

- Methods
  - Power systems engineering
  - Energy economics and policy
  - Optimization: Mathematical programming
  - Decision theory
  - Agent-based simulations
  - Game theory

***If the Only Tool You Have is a Hammer, then Every Problem Starts Looking Like a Nail…***

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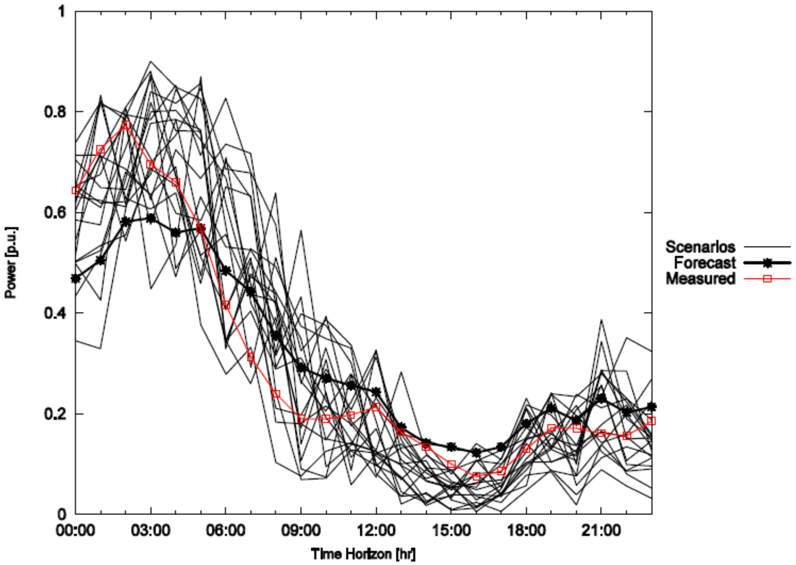
# Improved Market Operations with Renewables

- How do we best address increasing uncertainty and variability in system/market operations?
- Forecasting of wind and solar power
  - Importance of estimating forecast uncertainty (e.g. conditional kernel density estimation)
- Stochastic unit commitment
  - Minimizes expected cost across uncertainties
  - Implicit operating reserves
  - Most studies show significant benefits
  - Several challenges for real-world implementation
    - Computational aspect
    - Pricing and market implementation
  - Limited industry applications so far
- Improved operating reserve strategies
  - Dynamic/probabilistic reserves
  - New reserve categories




*Bessa et al. Renewable Energy*, 40(1): 29-39, *2012.*

| Study | Stochastic UC Cost Savings |
|---|---|
| Gröwe et, al. (1995) | 1.6% |
| Takriti et. al. (1996, 2000) | 0.4-4.0% |
| Tuohy et. al. (2008) | 0.6% |
| Wang et. al. (2008) | 1.3% |
| Pappala et. al. (2009) | 2.8-3.8% |
| Ruiz et. al. (2009, 2010) | 0.8-1.8% |
| Constantinescu et. al. (2011) | 1.0% |
| Wang et al. (2011) | 2.9 % |
| Zhou et al. (2013) | 1.7 % |
| Papavasilliou and Oren (2013a,b) | 1.9-5.4% |

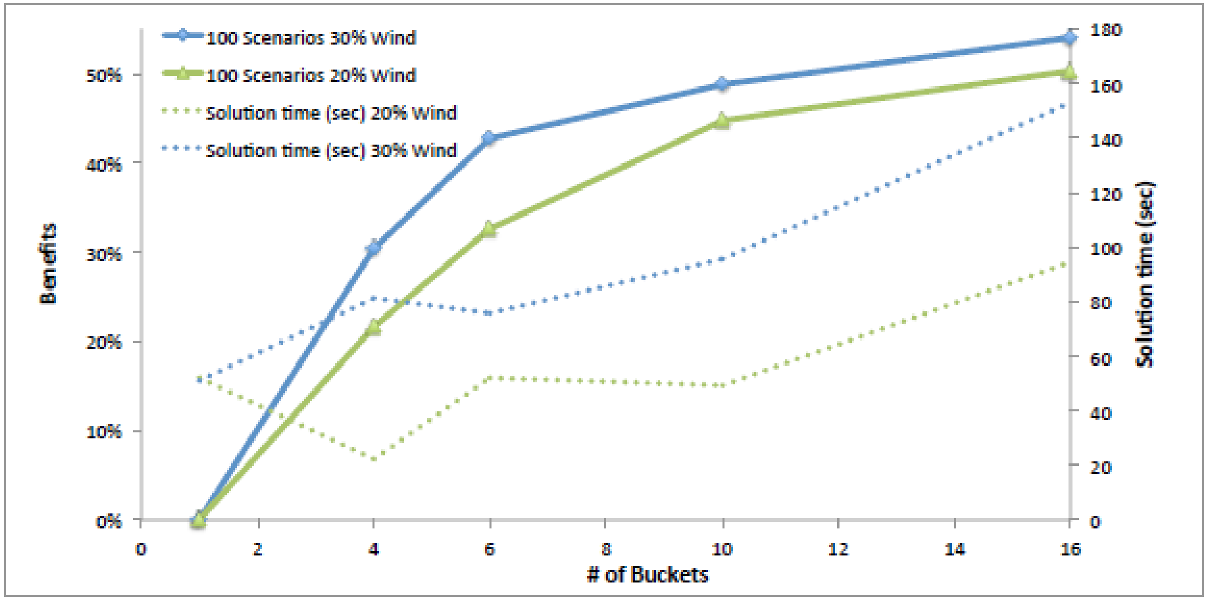
*Zhou et al., ANL/ESD-16/14, 2016.*

# An Improved Stochastic Unit Commitment Formulation

- Traditional two-stage stochastic unit commitment model
  - Unit commitment decisions are the same across all scenarios.
- New improved approach
  - Unit commitment decisions depend on wind forecast level ("bucket") and time segments, i.e., more flexible solutions, approaching a multi-stage formulation.

| Expected cost savings compared to two-stage model | |
|---|---|
| 6-bus | 0.8% |
| 24-bus | 1.4% |
| 118-bus | 0.4% |

Expected cost benefit* and solution time (6-bus)




* Percent of multi-stage benefit on 2-stage.

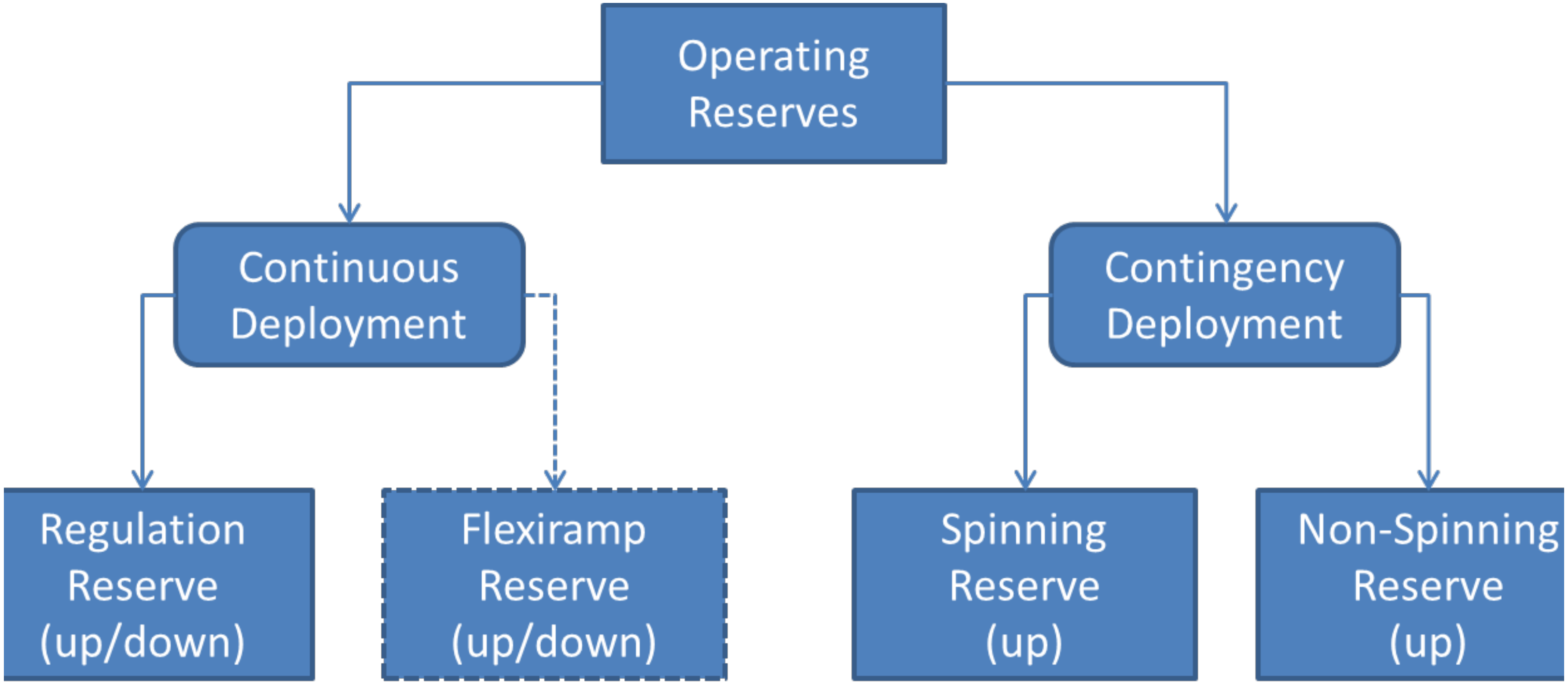
C. Uckun, A. Botterud, J. Birge, "An Improved Stochastic Unit Commitment Formulation to Accommodate Wind Uncertainty," *IEEE Transactions on Power Systems, 31 (4), 2507-2517, 2016.*

# A Short History of Operating Reserves with Renewable Energy

| Application | Method | Reference |
|---|---|---|
| **Probabilistic reserve estimates with renewable energy** | Meet probabilistic reliability target assuming Normal distribution for renewable energy forecast error | Söder 1993<br>Doherty and O'Malley 2005<br>Makarov et al. 2008 2009 |
| | Reserves in UC to minimize total system cost, including expected load shedding, assuming Normal distribution for forecast errors | Ortega-Vazquez et al. 2009 |
| | Reserve evaluation based on **probabilistic wind power forecasts** | **Matos Bessa 2011**<br>**Zhou and Botterud 2014** |
| | **Operating reserve demand curves** | **Hogan 2005**<br>**ERCOT 2013b**<br>**Zhou and Botterud 2014** |
| | New reserve products (flexi-ramp) | Wang, Hobbs 2014, 2015 |
| | Reserves in integration studies and industry developments | Ackerman et al. 2007<br>Ela et al. 2011<br>Holttinen et al. 2013<br>Enernex 2010<br>GE Energy 2010<br>Lew et al. 2013<br>Mills et al. 2013<br>ERCOT 2013a<br>ERCOT 2013b<br>Ellison et al. 2012<br>Ela et al. 2014 |

*Zhou et al., ANL/ESD-16/14, 2016.*

# *Evolving U.S. Market for Operating Reserves*

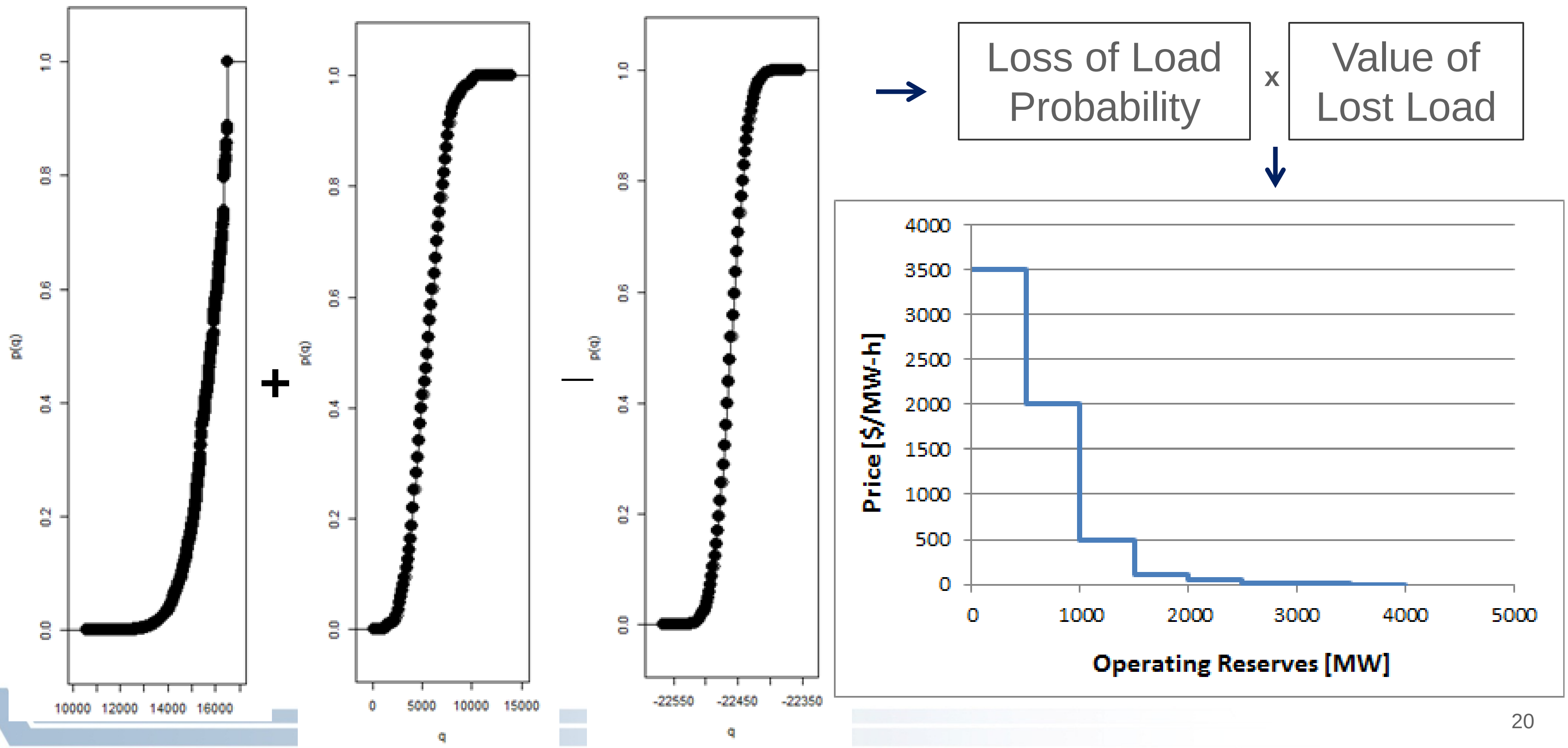



- Regulation reserve: Pay for performance
- “Flexi-ramp reserves” to ensure sufficient ramping capability available in real-time
  - California ISO (CAISO)
  - Midcontinent ISO (MISO)

# A Dynamic Operating Reserves Demand Curve (ORDC)

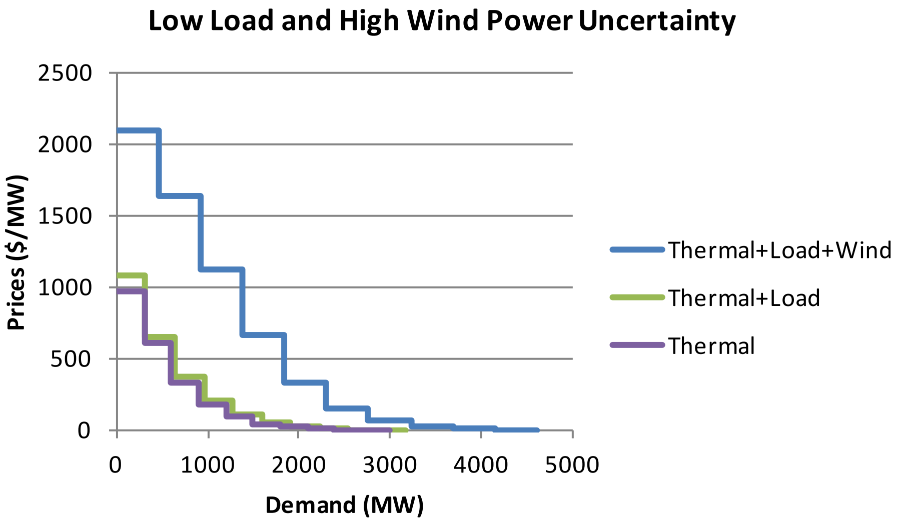
- Consider the uncertainties from load and supply
  - Probabilistic wind power forecast based on Kernel Density Estimation (Bessa et al. 2012)
- Estimate the risk of supply shortage for system
- Link the expected cost of this risk to the price to pay for reserves (Hogan 2005)

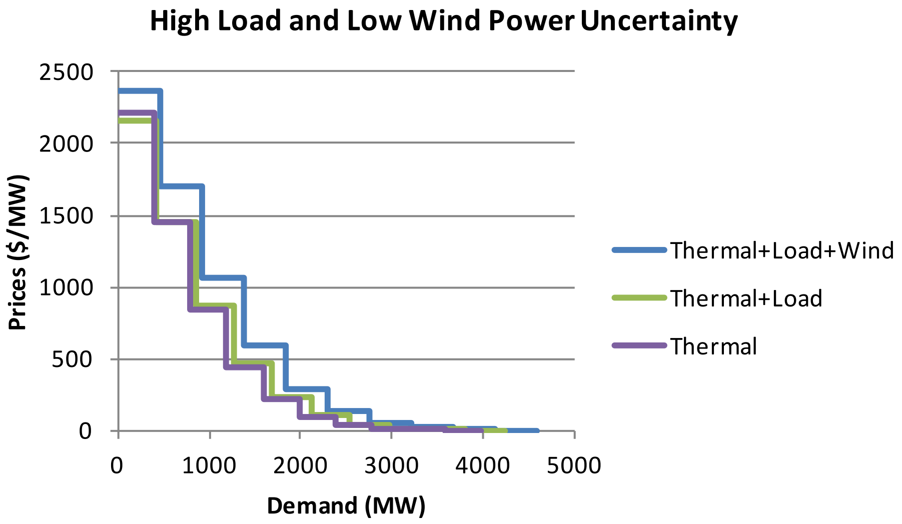
*Thermal generators* *Wind power* *Load*



# ORDCs Depend on the Wind Power Forecast

- Operating reserve demand curves for more efficient market pricing
  - Demand for reserves is dynamic and varies by situation (e.g. wind power forecast uncertainty)



# Unit Commitment with ORDCs

**Objective:**

$$\text{Min} \sum_{t,i}[fc_{t,i} + C(ens_t) + sc_{t,i}] - \sum_{t} pfr_t$$

Expected utility of operating reserves

**Constraints:**

(1) Load-generation balance:

$\sum_i p_{t,i} + wg_t + ens_t = D_t \ \forall t$

(2) Wind generation dispatch

$wg_t \leq W_t \ \ \forall t$

(3) Generation

$p_{t,i} = PMIN_i \times u_{t,i} + \sum_k delta_{t,i,k} \ \ \forall t, i$

$p_{t,i} \leq pbar_{t,i} \ \ \forall t, i$

$pbar_{t,i} \leq PMAX_i \times u_{t,i} \ \ \forall t, i$

(4) Energy block

$delta_{t,i,k} \leq PR_{i,k} \ \ \forall i, k$

(5) Spin/non-spin reserve balance

$pbar_{t,i} - p_{t,i} \geq sr_{t,i} + nsrn_{t,i} \ \ \forall t, i$

$nsrn_{t,i} \leq NSRRESPONSETIME \times MSR_i \times u_{t,i} \ \ \forall t, i$

$nsrf_{t,i} \leq QSC_i \times (1 - u_{t,i}) \ \ \forall t, i$

$deltasrd_{t,k} \leq SRDCR_k \ \ \forall t$

$\sum_i sr_{t,i} \geq SRRATIO \times \sum_k deltsrd_{t,k} \ \ \forall t$

$\sum_i (nsrn_{t,i} + nsrf_{t,i}) \geq NSRRATIO \times \sum_k deltsrd_{t,k} \ \ \forall t$

$sr_{t,i} \leq SRRESPONSETIME \times MSR_i \times u_{t,i} \ \ \forall t, i$

(6) Utility from reserve demand

$pfr_t = \sum_k SRDC_k \times deltsrd_{t,k}, \forall t$

(7) Shut down and start up

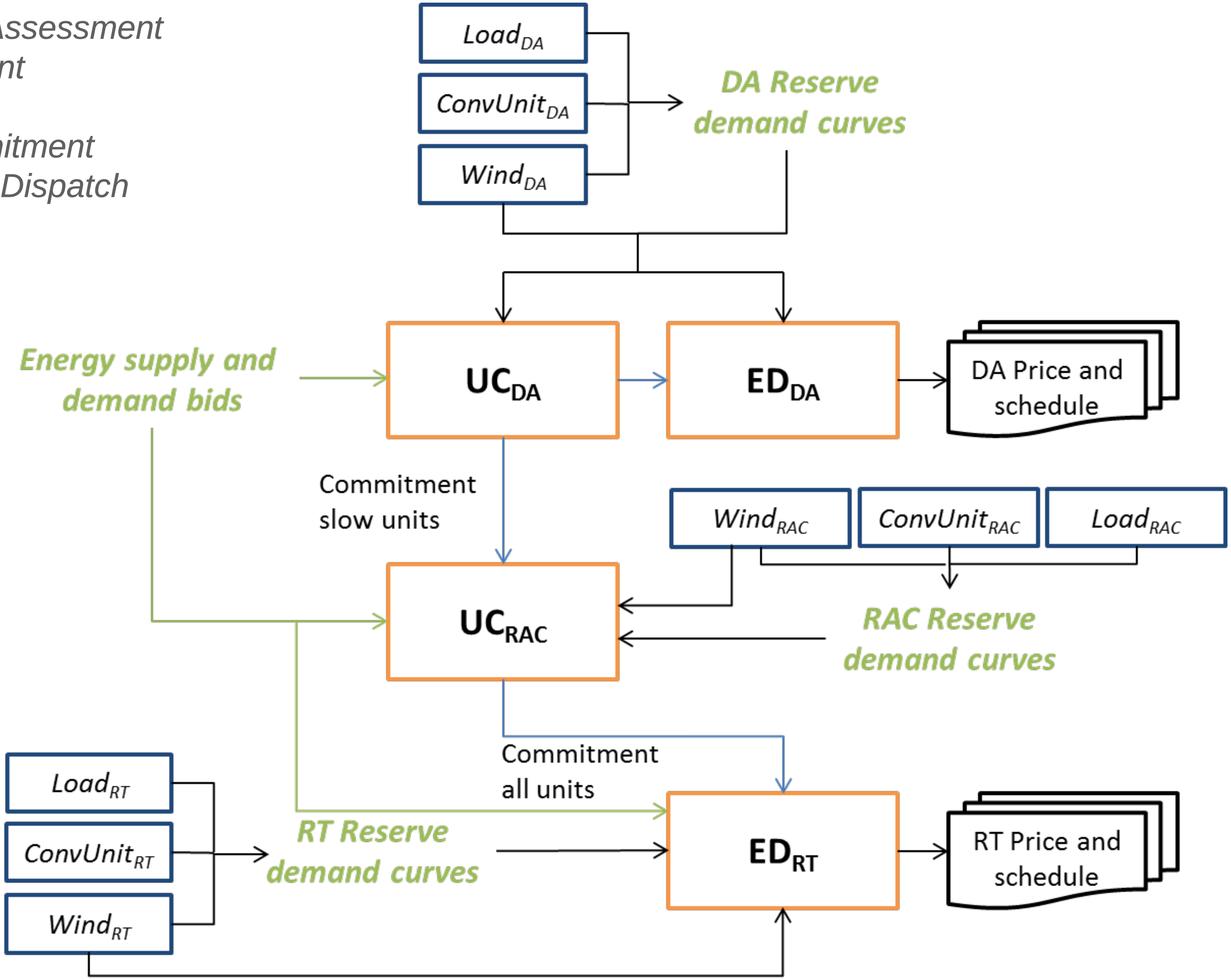
(8) Minimum up and startup

(9) Minimum down and shutdown

(10) Ramp up and Ramp down

# Simulating Electricity Market Operations

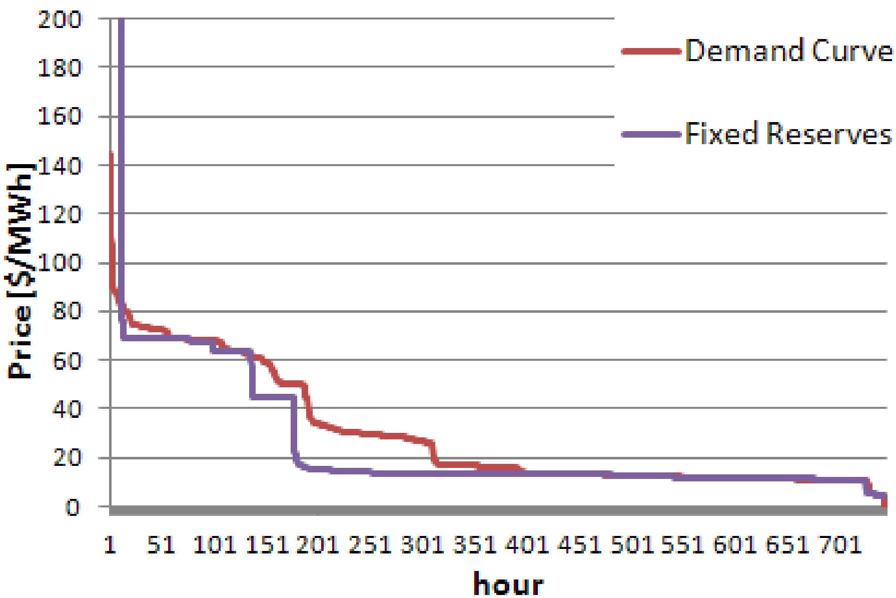
*DA: Day-ahead*
*RAC: Reliability Assessment Commitment*
*RT: Real Time*
*UC: Unit Commitment*
*ED: Economic Dispatch*



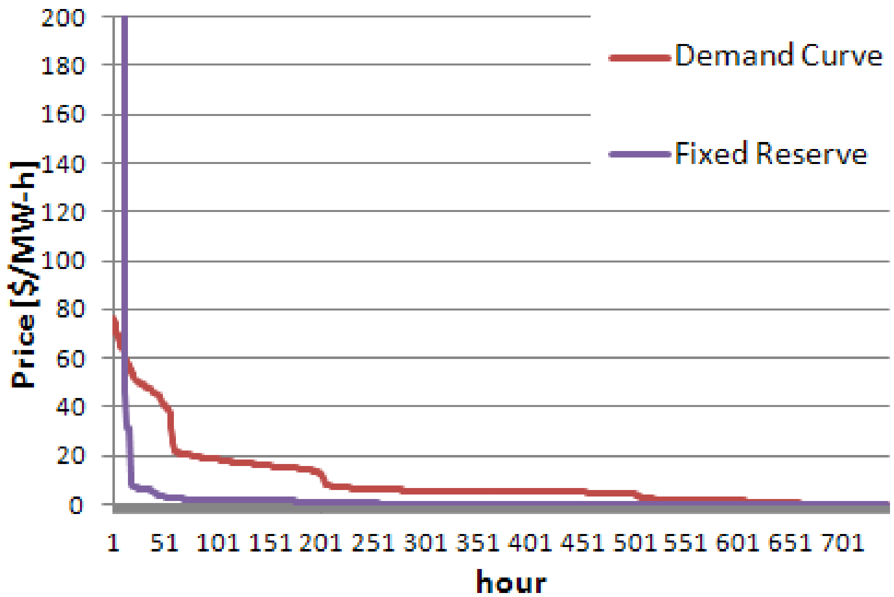
# OR Demand Curves: Implications for Market Prices

- Results from simulation of co-optimized electricity market (Illinois case)

Energy price distribution (July)




Reserves price distribution (July)




- Benefits of a dynamic demand curve for operating reserves
  – Gives higher prices for energy and reserves in most hours, fewer extreme price spikes
  – Stabilizes revenue stream for thermal generators
  – Better reflects wind power forecast uncertainty in prices
  – Adds demand flexibility to the scheduling and dispatch

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

# ORDCs have been Introduced in the ERCOT Market

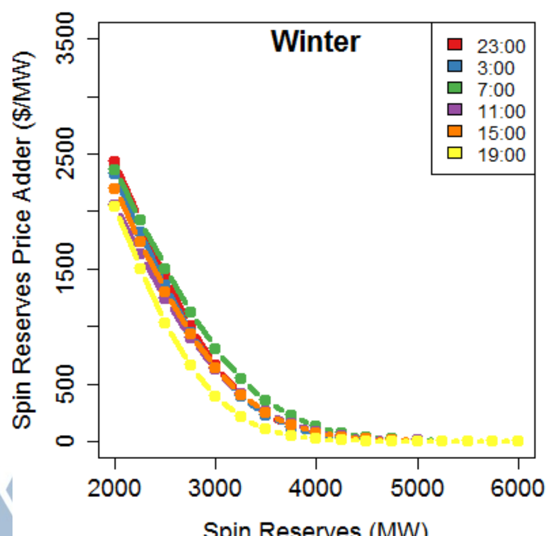
- ERCOT (Texas) implemented an ORDC in the real-time market June 1st 2014
  - Price Adders for Online and Offline Reserves
  - Online Reserve Price Adder (RTORPA) is added to the LMP

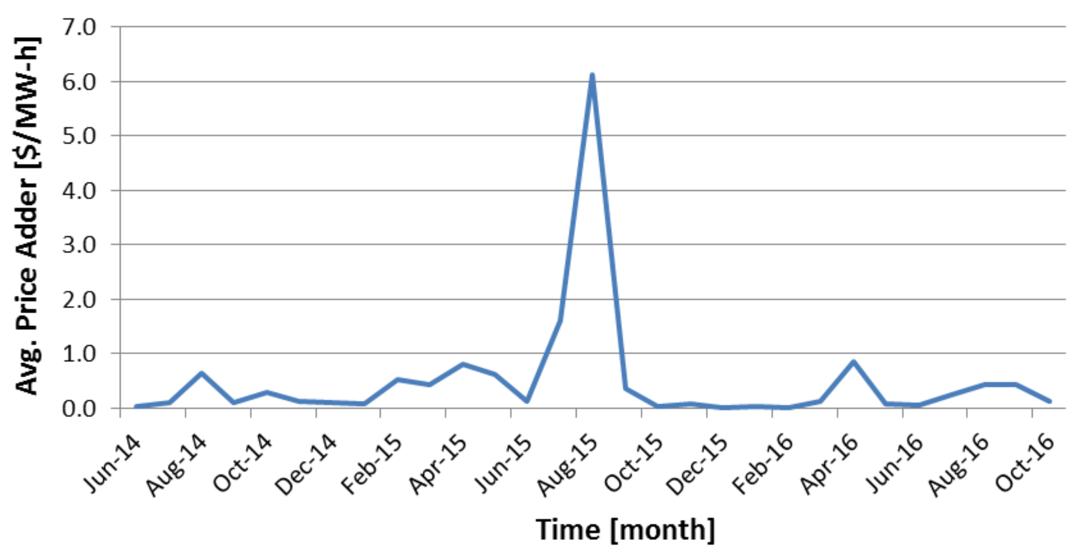
VOLL LOLP

$$RTORPA = P_S = v * 0.5 * \pi_S(R_S) + P_{NS}$$

$$RTOFFPA = P_{NS} = v * (1 - 0.5) * \pi_{NS}(R_{SNS})$$

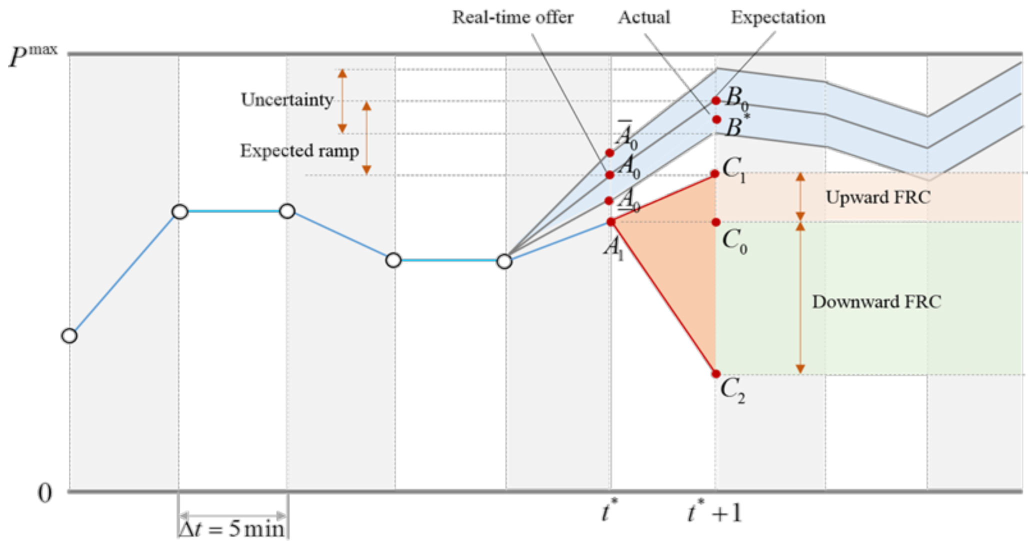
  - *"The price after the addition of RTORPA to LMPs approximates the pricing outcome of Real-Time energy and Ancillary Service co-optimization since RTORPA captures the value of the opportunity cost of reserves based on the defined ORDC."* ERCOT 2014



# Wind Power Providing Flexible 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 at a sub-optimal operating point, 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.




**Including the WPPs in the real-time market as FRC providers**

$$\hat{f} = \sum_{t\in T}\sum_{i\in FG} u_{i,t} c_i^{SU} + \sum_{s\in S}\rho_s \left[\Delta t \sum_{t\in T}\sum_{i\in G} C_i\left(p^g_{i,t,s}\right) + VOLL\cdot\sum_{t\in T}\Delta l_{t,s} + \omega\left(\Delta r^u_t + \Delta r^d_t\right) + \sum_{t\in T}\sum_{j\in W}\left(\pi^u_j r^{w,u}_{j,t,s} + \pi^d_j r^{w,d}_{j,t,s}\right)\right]$$

**Considering the impact of uncertainty**

**Compensating the WPPs for providing FRCs**

$$\sum_{i\in G} r^{g,u}_{i,t,s} + \sum_{j\in W} r^{w,u}_{j,t,s} \ge \left[\hat{L}_{t+1,s} - \sum_{i\in G^{II}}\left(\Delta p^{g,su}_{i,t+1,s} - \Delta p^{g,sd}_{i,t+1,s}\right) - \sum_{j\in W}\hat{p}^w_{j,t+1,s}\right] - \left(L_{t,s} - \Delta l_{t,s} - \sum_{j\in W}\tilde{p}^w_{j,t,s}\right) + \xi^u : \beta^u_{t,s}, \forall t, \forall s$$

$$\sum_{i\in G} r^{g,d}_{i,t,s} + \sum_{j\in W} r^{w,d}_{j,t,s} \ge -\left[\hat{L}_{t+1,s} - \sum_{i\in G^{II}}\left(\Delta p^{g,su}_{i,t+1,s} - \Delta p^{g,sd}_{i,t+1,s}\right) - \sum_{j\in W}\hat{p}^w_{j,t+1,s}\right] + \left(L_{t,s} - \Delta l_{t,s} - \sum_{j\in W}\tilde{p}^w_{j,t,s}\right) + \xi^d : \beta^d_{t,s}, \forall t, \forall s$$

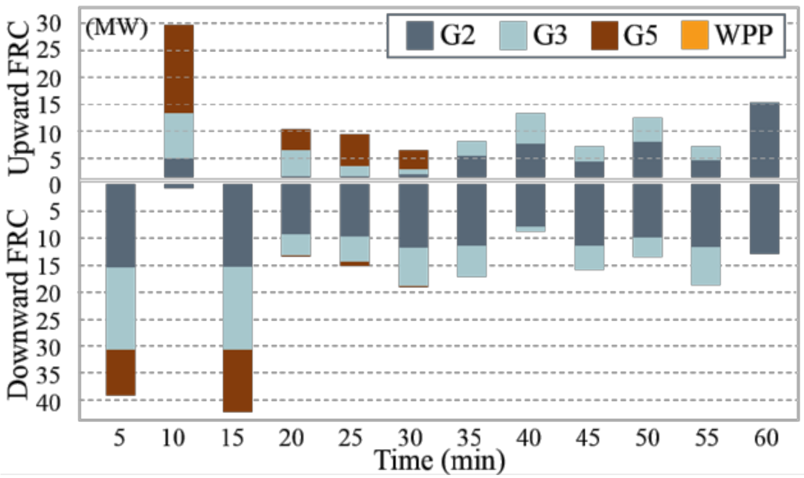
**Overall FRC supply** | **Certain system-wide variation** | **Margin for uncertain variation**

*Chen et al., IEEE Trans. Power Systems, in press.*

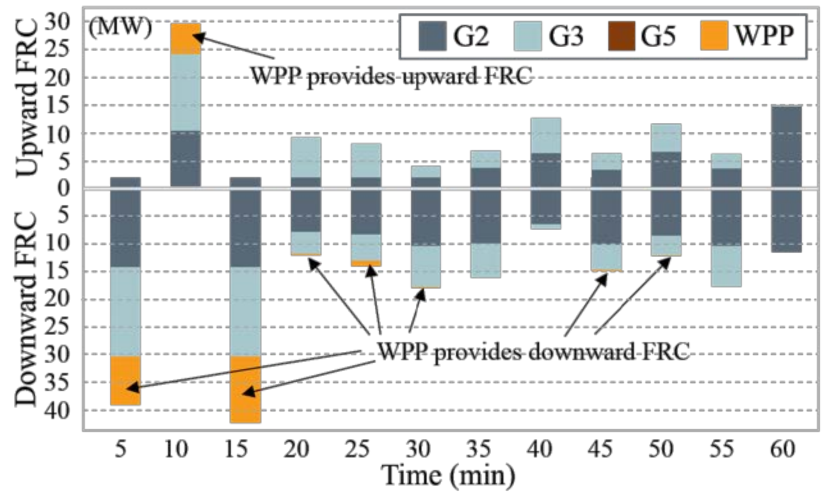
# *Wind Power Providing Flexible Ramp Capacity (FRC)*

In the case system, by utilizing the WPPs' capability of providing FRC, the commitment of expensive fast-start G5 is effectively reduced. Meanwhile the WPPs are compensated for providing the service, the overall system cost is reduced for most of the cases.

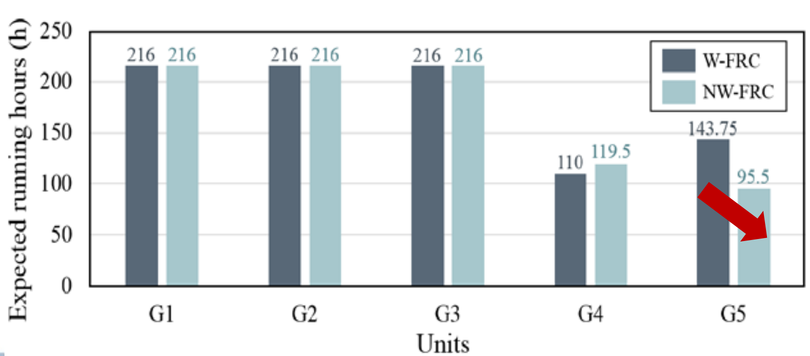
**WPP not providing FRC: G5 is committed**



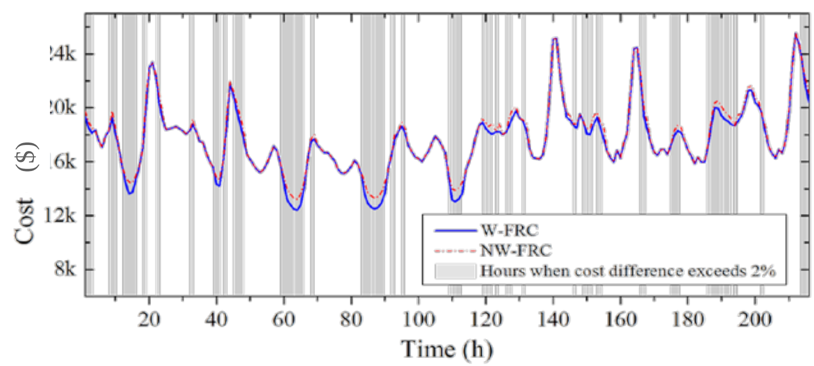

**WPP providing FRC: G5 is not committed**




**The commitment of G5 is effectively reduced**




**System cost is reduced for most of the cases**




*Chen et al., IEEE Trans. Power Systems, in press.*

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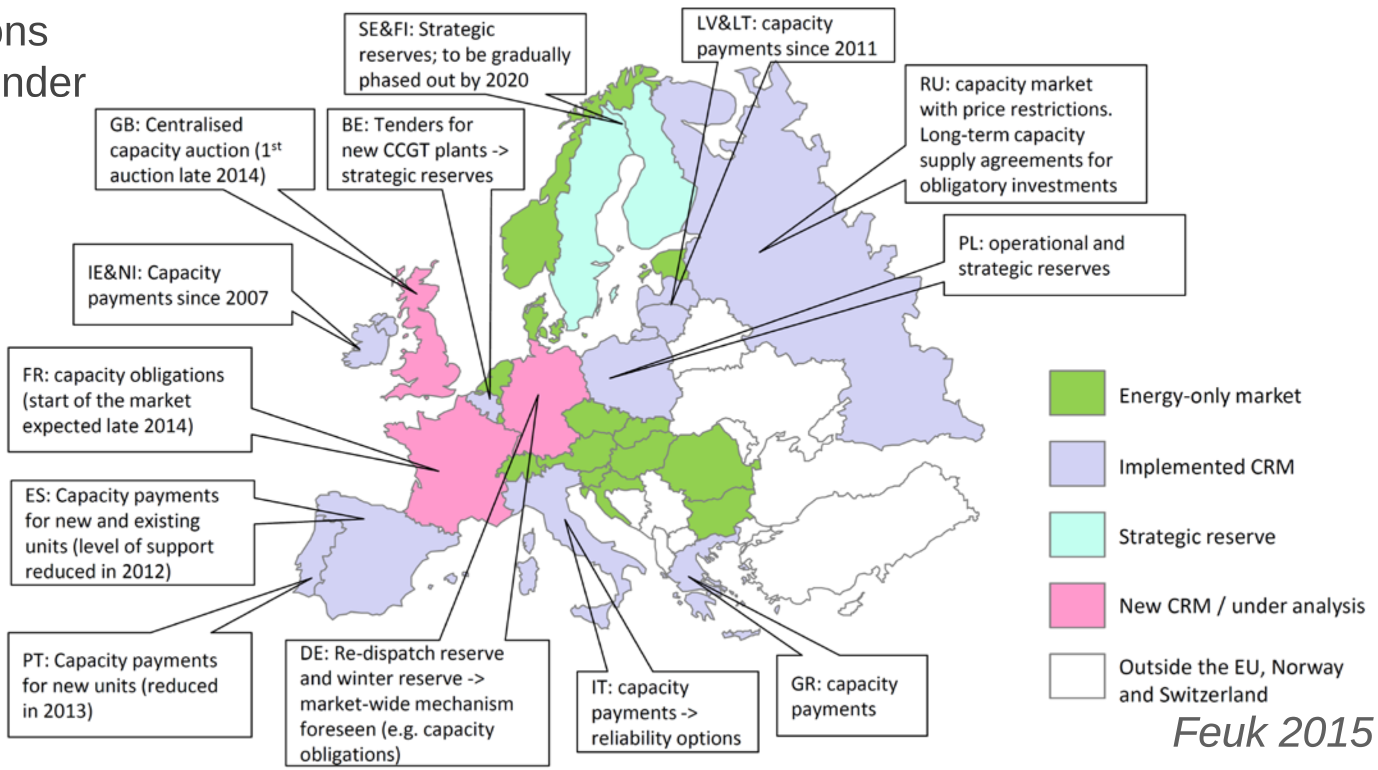
# Resource Adequacy and Capacity Mechanisms

- Open questions
  - Do we need specific resource adequacy mechanisms?
  - Do we need to incentivize capacity with specific attributes?
- Europe
  - Multiple solutions implemented/under consideration

- United States
  - Capacity markets
    - PJM, NE-ISO, NYISO, MISO
  - Capacity obligations
    - CA-ISO
  - Energy Only
    - ERCOT/Texas
  - Integrated resource planning




Feuk 2015

# Generation Expansion and Capacity Adequacy in Texas (ERCOT market)

- Model three different market polices to value reserves, energy and capacity
  - 1) Operating Reserves Demand Curve
    - ERCOT curves, but co-optimization
  - 2) Fixed Reserves Scarcity Pricing
    - Used in most U.S. markets
    - We assume:
      - $100/MW-h spin-up
      - $500/MW-h total reserve
  - 3) Capacity Payments
    - $40/kW-year
    - No reserve scarcity pricing

- Case Study of ERCOT market in Texas
  - 4 thermal unit types (Nuclear, Coal, NGCC, NGCT)
  - 2013 ERCOT wind and load profile
  - 2024 total load projection (15% growth)
  - Wind varies from 10% to 40% of total demand

| Parameter | Value |
|---|---|
| Peak Load (MW) | 77,471 |
| Existing Generation Capacity (MW) | 73,380 |
| Nuclear | 4,400 |
| Coal | 19,500 |
| NGCC | 43,600 |
| NGCT | 5,880 |
| Maximum Wind Resource Capacity Factor | 33.0% |

# Centralized Generation Expansion: Formulation

## ORDC

Expansion (Integer) — Commitment (Integer)

$$\min \sum_{i \in I} u_i \cdot (C_i + F_i) \cdot \overline{P_i} + \sum_{i \in I} \sum_{t \in T} MC_i \cdot g_{i,t} + SUC_i \cdot y_{i,t} + SDC_i \cdot x_{i,t} + NLC_i \cdot z_{i,t} \cdot \overline{P_i}$$
$$+ \sum_{t \in T} VOLL \cdot es_t - PTC \cdot wg_t - \sum_{t \in T} RBS_t[Rs_t] + RBNS_t[Rns_t]$$

## Reserve Scarcity Pricing (FRSP) / Capacity Payment (CP)

$$\min \sum_{i \in I} u_i \cdot (C_i + F_i - CP) \cdot \overline{P_i} + \sum_{i \in I} \sum_{t \in T} MC_i \cdot g_{i,t} + SUC_i \cdot y_{i,t} + SDC_i \cdot x_{i,t} + NLC_i \cdot z_{i,t} \cdot \overline{P_i}$$
$$+ \sum_{t \in T} ESC \cdot es_t + SRSC \cdot srs_t + NRSC \cdot nrs_t$$

$$\sum_{i \in I} rs_{i,t} + wr_t + rss_t = RRs_t \quad \forall \ t \in T$$

$$\sum_{i \in I} (rs_{i,t} + rns_{i,t}) + wr_t + rnss_t = RRs_t + RRns_t \quad \forall \ t \in T$$

Shadow Price

**Reserve targets are based on ORDC results.**
Spin: $15/MW-h
Non-Spin: $.01/MW-h

**Energy/reserve prices in each period are set equal to the marginal cost/benefit of their provision**

# Centralized Generation Expansion: Formulation

## Load Balance

$$\sum_{i \in I} g_{i,t} + wg_t + es_t = D_t$$ → LMP Shadow Price

## Unit Reserves

$$rs_{i,t} \leq z_i \cdot \overline{P_i} \cdot SPR_i \qquad \forall\ i \in I, s \in S, t \in T$$

$$rns_{i,t} \leq (u_i - z_i) \cdot \overline{P_i} \cdot NSR_i \qquad \forall\ i \in I, s \in S, t \in T$$

## Thermal Output

$$g_{i,t} + rs_{i,t} \leq z_{i,t} \cdot \overline{O_i} \qquad \forall\, i \in I, t \in T$$

$$g_{i,t} \geq z_{i,t} \cdot \underline{O_i} \qquad \forall\, i \in I, t \in T$$

## Wind Balance

$$wg_t + wr_t + wc_t = W_t \qquad \forall\ t \in T$$

## Ramping

$$g_{i,t} \leq g_{i,t-1} + z_{i,t} \cdot RU_i \qquad \forall\, i \in I, t \in T \neq 1$$

$$g_{i,t} \geq g_{i,t-1} - z_{i,t-1} \cdot RD_i \qquad \forall\, i \in I, t \in T \neq 1$$

## Unit Commitment

$$z_{i,t} = z_{i,t-1} + y_{i,t} - x_{i,t} \qquad \forall\ i \in I, t \in T \neq 1$$

$$z_{i,t} \leq u_i \qquad \forall\ i \in I, t \in T$$

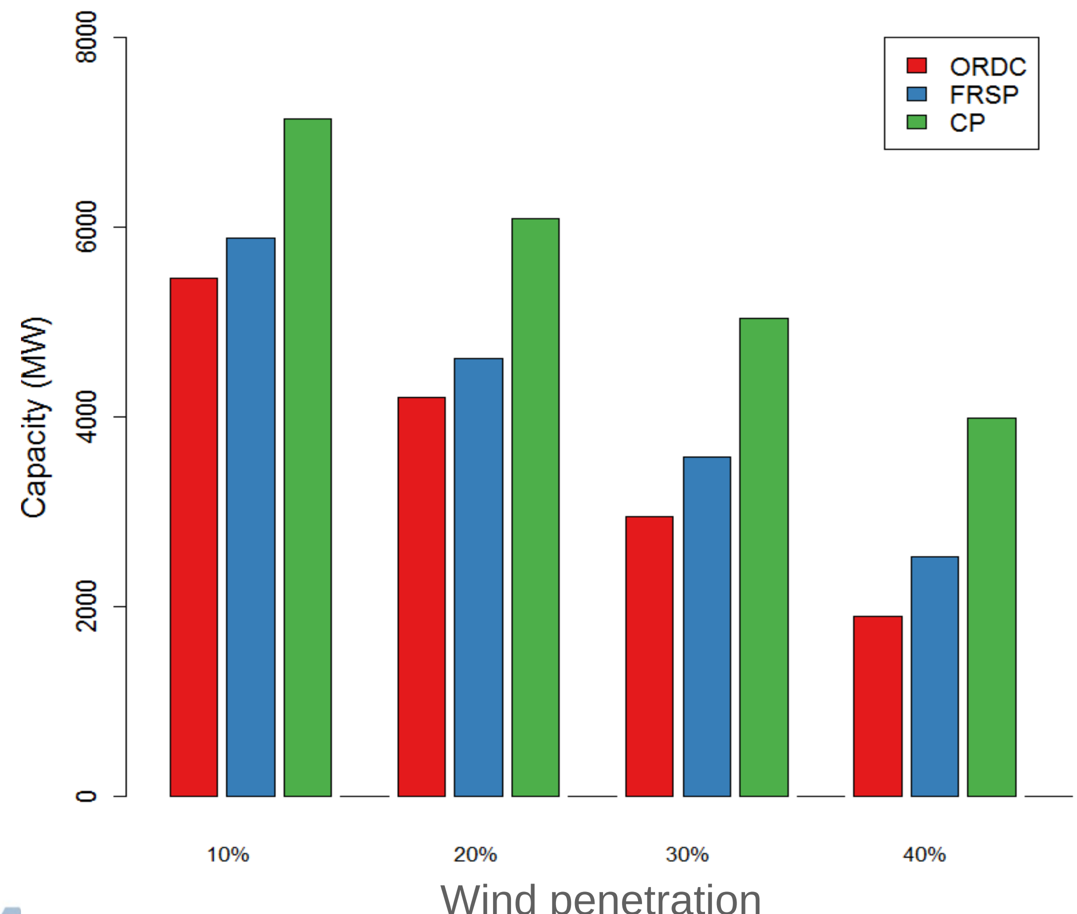
$$x_{i,t},\ y_{i,t},\ z_{i,t} \geq 0 \quad \forall\ i \in I, t \in T$$

- **Integer variables for expansion and commitment**
- **Significant reduction in computation time (up to 5000x*)**
- **Enables solving for full year of operations (8760 hourly periods)**

* B. Palmintier and M. Webster, “Impact of unit commitment constraints on generation expansion planning with renewables,” in *2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 1–7.

# Results: Capacity Expansion

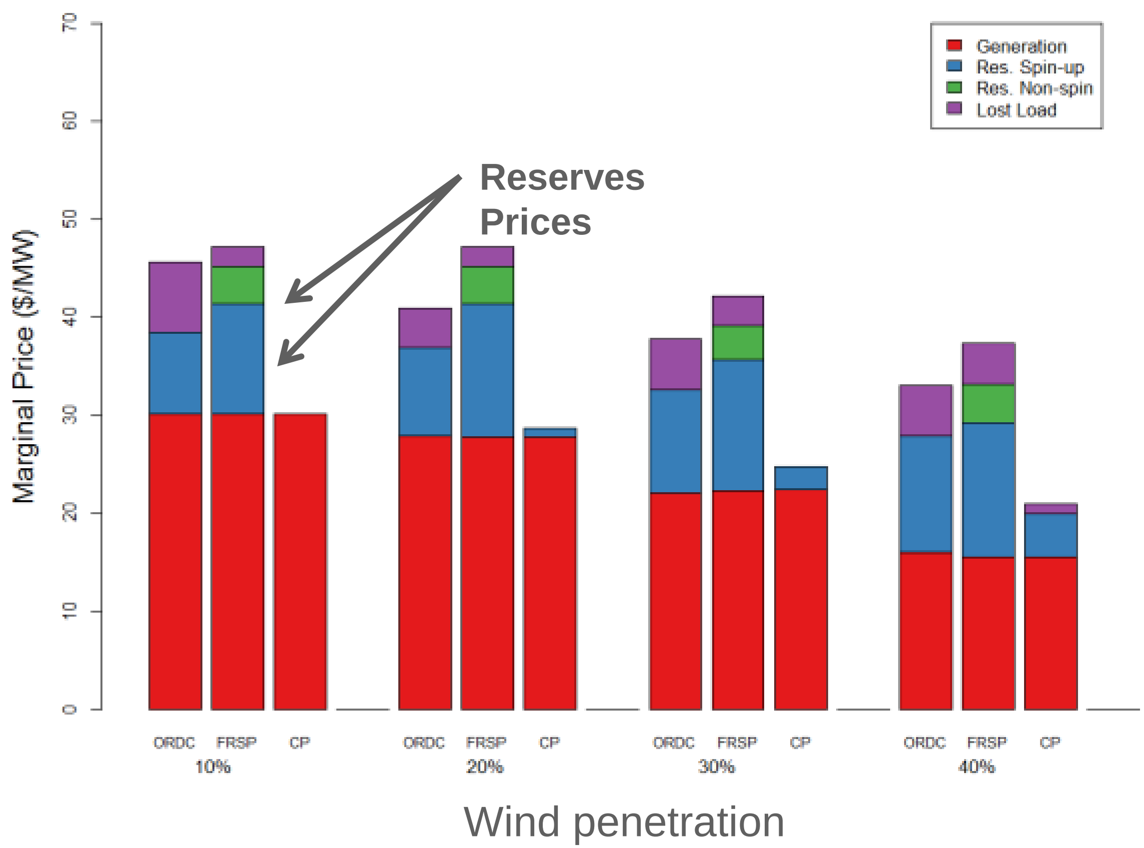
- Only new NGCT capacity is developed
  - CP results in most new capacity
  - ORDC and FRSP are comparable




ORDC – operating reserve demand curve
FRSP – fixed reserve scarcity pricing
CP – capacity payment

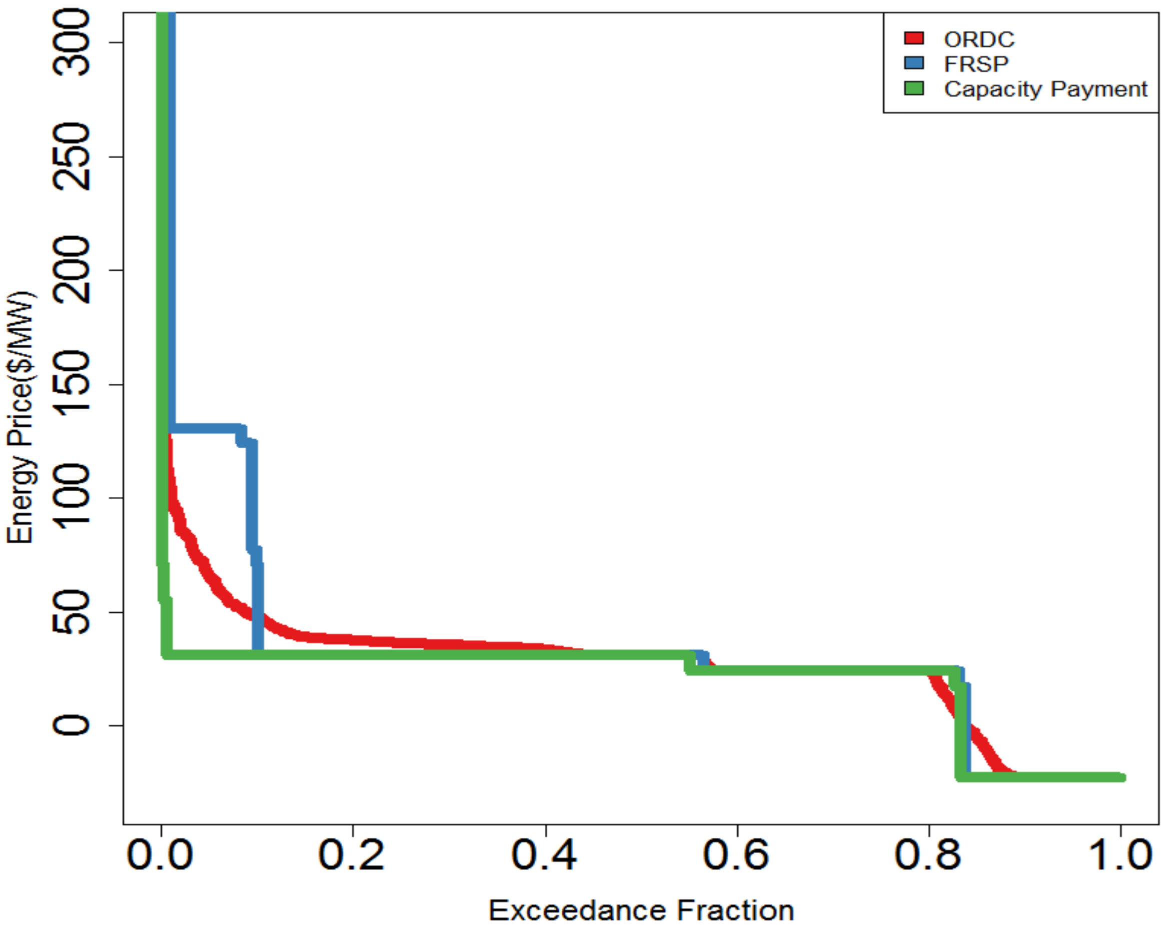
# Results: Average Prices

- **Prices drop with increasing wind**
- **ORDC > CP**
  - CP has no reserves pricing mechanism
    - Lower prices
  - More capacity under CP
    - Essentially no lost load
- **FRSP > ORDC**
  - Higher reserve prices
    - Scarcity price spikes
    - Mostly non-spin
  - Less frequent lost load
    - Few hours, large price impact



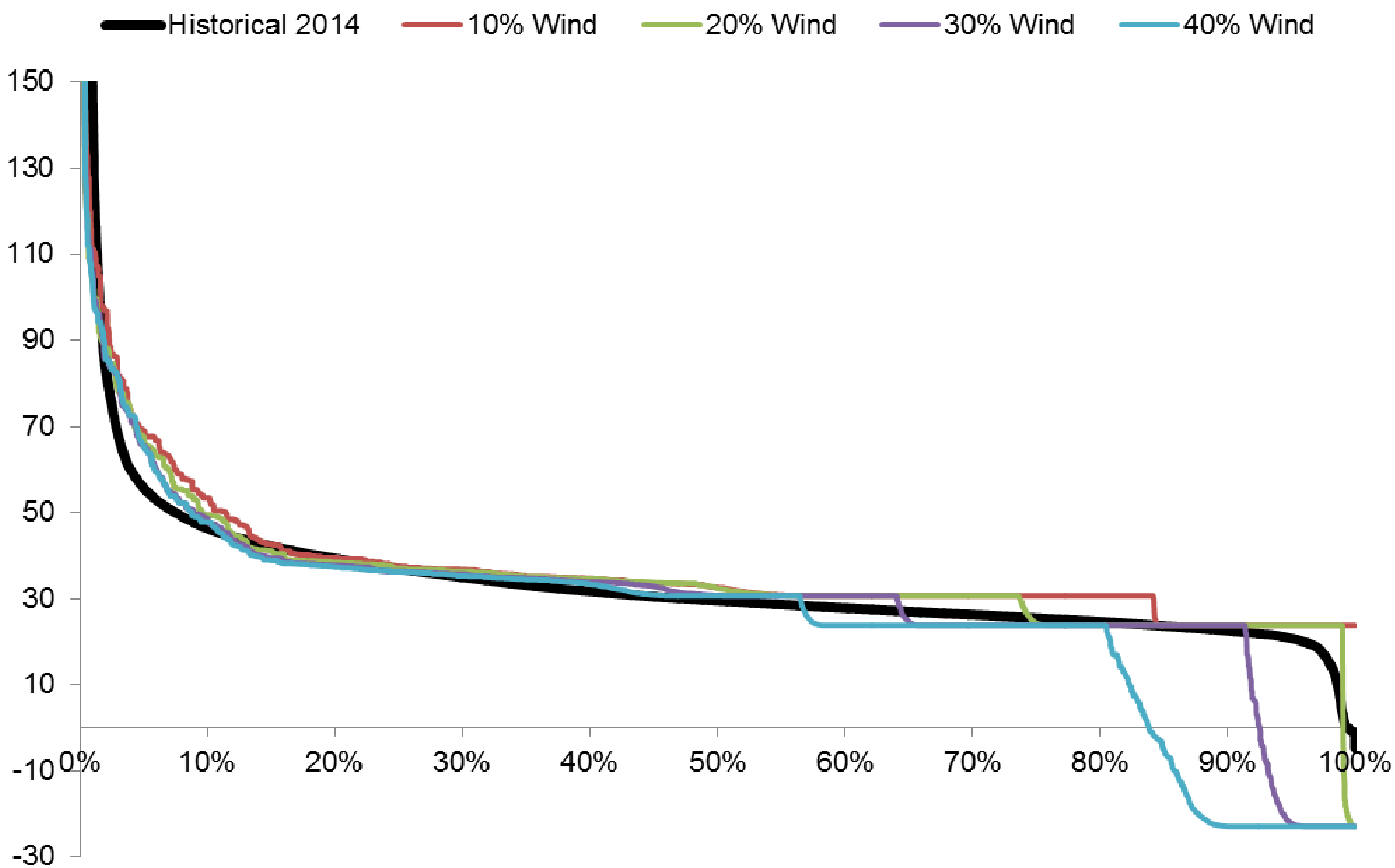
# Results: Annual Price Exceedance Curve (40% wind)

- ORDC -> More continuous price spectrum

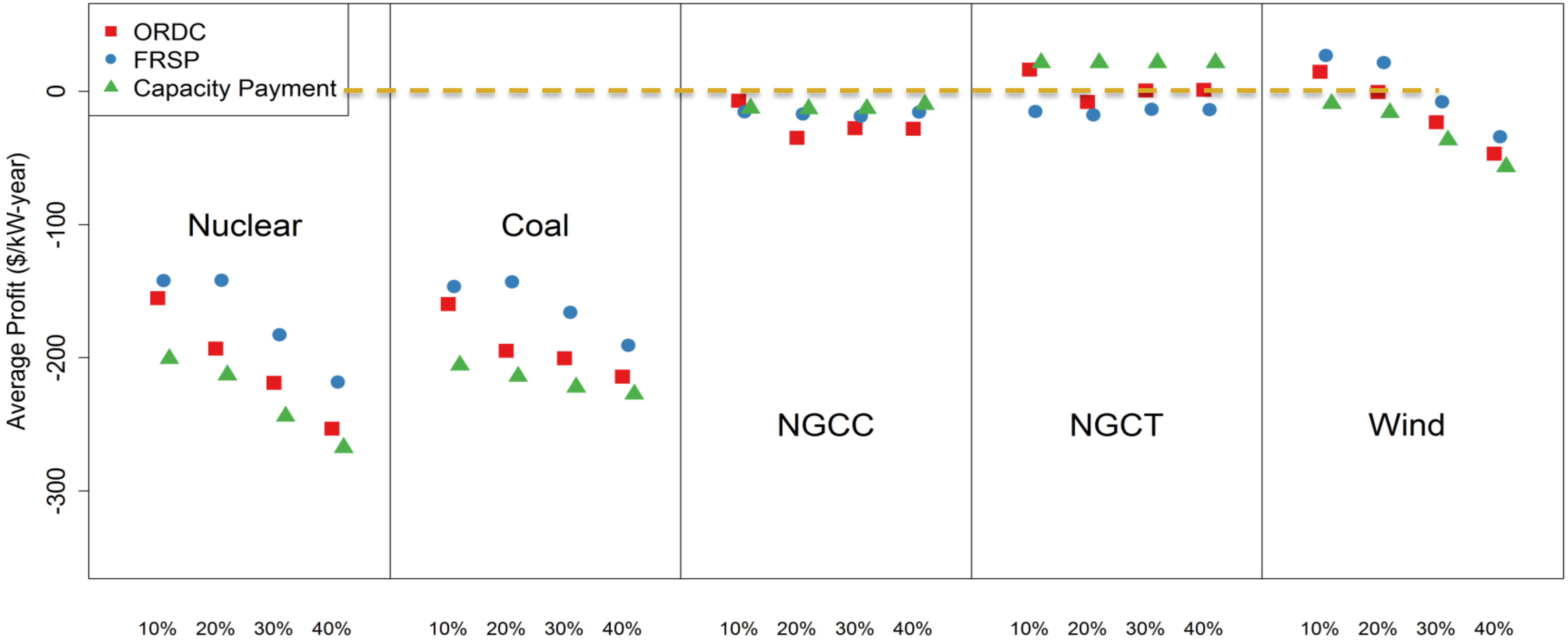



ORDC – operating reserve demand curve
FRSP – fixed reserve scarcity pricing
CP – capacity payment

# ORDC Historical Comparison



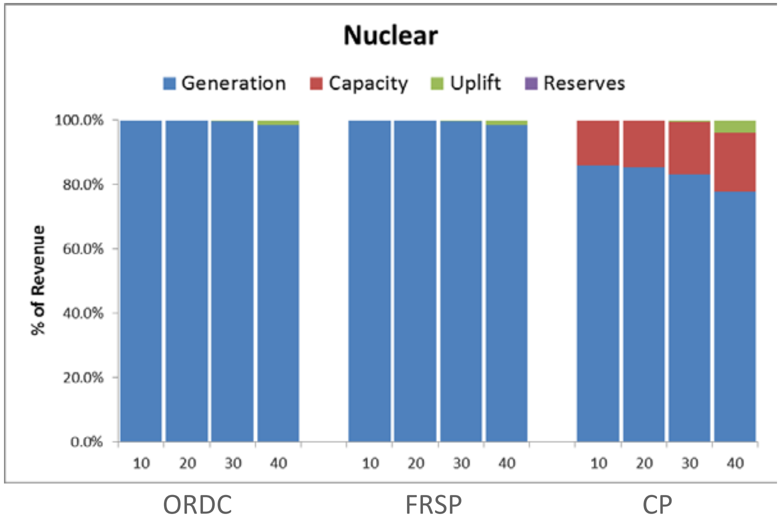
# Results: Generator Profits

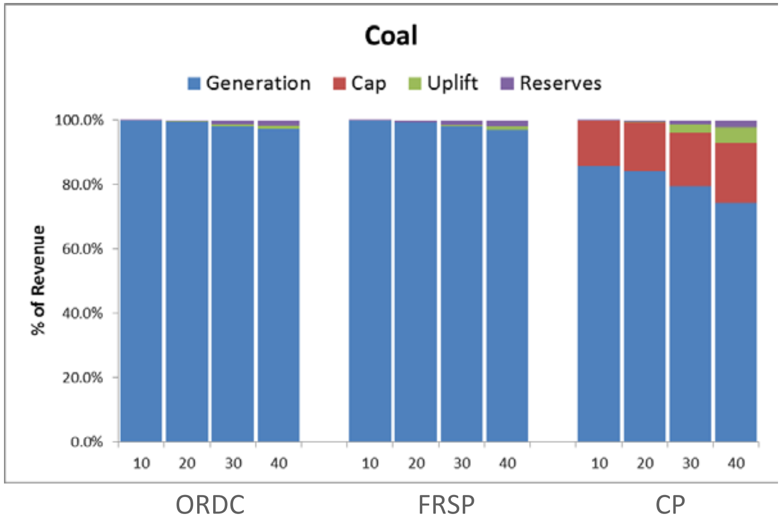


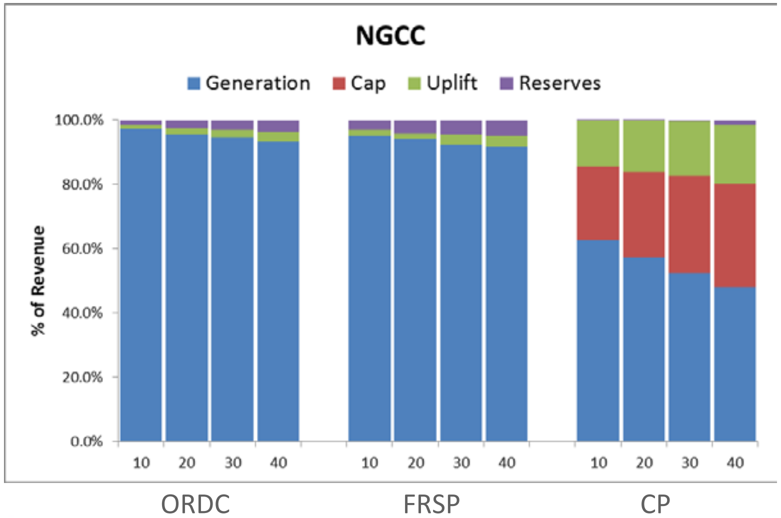

- Nuclear, Coal and Wind profits decrease with increasing wind
  – More exposed to lower off-peak prices
- Gas units (NGCT, NGCC) receive additional revenues from providing reserves
- The optimal investment choice (NGCT) breaks even under all mechanisms for all wind penetration levels

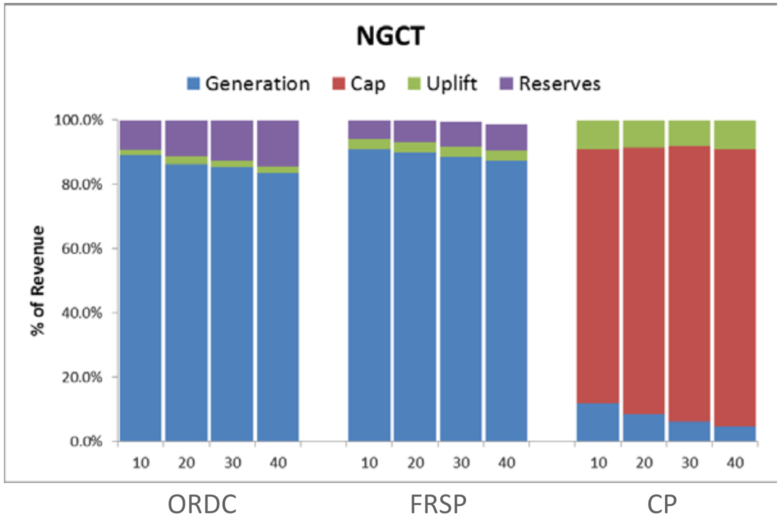
*Levin and Botterud 2015, Energy Policy*, 87: 392–406, 2015.

# Revenue by Source for each Technology



# Towards Improved Electricity Markets

- Several measures could improved the functioning of electricity markets (supporting energy only markets)

## United States

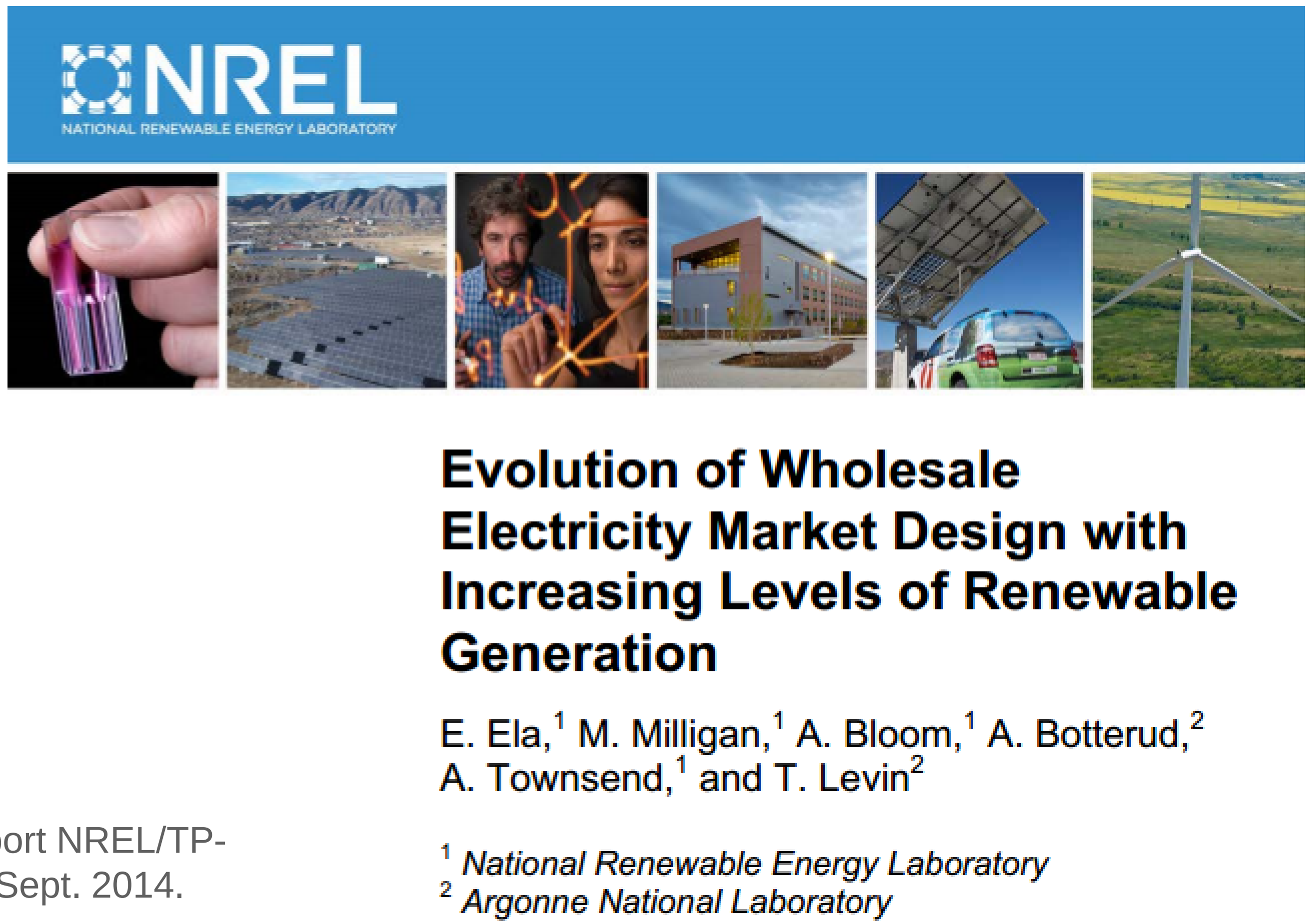
- Gradual removal of RES subsidies/ tax credits and introduction of $CO_2$ pricing at national level
- Liquid markets for long-term contracts: hedging for both generators (low/negative prices) & customers (high/price spikes)
- Implementation of Intraday-market for balancing
- Higher time resolution of real-time market settlements (5 min)
- Revision of ancillary services markets (product definitions and quantities)
- Better coordination between ISOs
- others

## Europe

- Gradual removal of RES subsidies and correct $CO_2$ price signals
- Flow-based cross-border transmission capacity allocation and auctioning (improved market coupling of the different market zones)
- Price zones that better reflect congestion patterns
- „Imbalance netting“ to avoid counteracting activations of control zones in frequency regulation
- Shortening time frames in the Intraday-market
- Dispatchable renewables
- Co-optimization of energy and reserves
- others

# Electricity Market Design with Renewable Energy

- 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**

E. Ela,[1] M. Milligan,[1] A. Bloom,[1] A. Botterud,[2] A. Townsend,[1] and T. Levin[2]

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

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

# Outline

- Background
  - Renewable energy penetration levels
  - Electricity market operations
  - Core research questions
- Addressing Renewables in Short-term Operations
  - Operating reserve demand curves
- Addressing Renewables in Long-term Planning
  - Generation Expansion and Revenue Sufficiency
- Concluding Remarks

# Concluding Remarks

- Electricity markets and renewable energy
  - Fundamental challenges the same in Europe and United States: uncertainty and variability
  - Implications for operations, planning, and markets
  - Flexibility is key, but solutions differ
  - More advanced electricity markets in the US, more support for renewables in Europe
  - Physical complexity vs. economic transparency in market design

- Many solutions to variable renewable energy integration challenges
  - Supply flexibility, demand response, energy storage
  - Forecasting, operational practices, market design
  - No silver bullet: Ideally, the most cost effective solutions should prevail
  - Lessons can be learned from both Europe and United States
    - Intraday markets, long-term markets (Europe -> United States)
    - Co-optimization energy/reserves, locational pricing, dispatchable renewables (United States -> Europe)

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## Additional Publications and Information

Wind power forecasting and electricity markets project: http://ceeesa.es.anl.gov/projects/windpowerforecasting.html

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# Electricity Markets and Renewable Energy: United States vs. Europe


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