FREEDM
SYSTEMS CENTER

GridWrx Lab

Providing Frequency Regulation Services using Energy Storage Systems

Professor Ning Lu and Yao Meng

Please visit my homepage: https://sites.google.com/a/ncsu.edu/ninglu/

Prepared for IEEE IAS/PES/WIE, Oct. 24, 2018

1. Background
2. Regulation Services
3. Modeling of Energy Storage Devices
4. Cost Benefit Study: Regulation Services
5. Fast Frequency Response Services
6. Provision of Frequency Response Services

Research Areas

- PV Integration
- Energy Storage
- Electric Power Distribution System Analysis
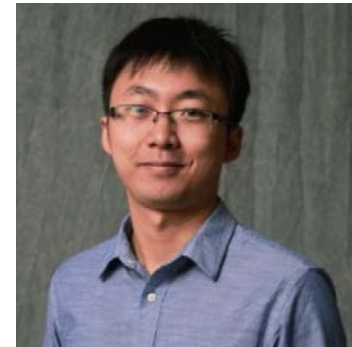- Energy Management Systems
- Microgrid
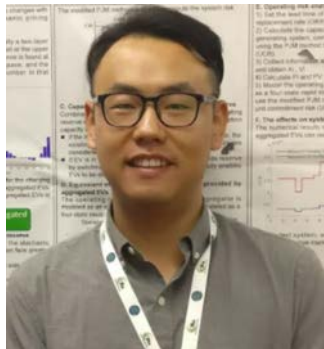- Distribution automation
- Advanced Data Analytics

Ning Lu
nlu2@ncsu.edu

David Lubkeman
dllubkem@ncsu.edu

Mesut Baran
baran@ncsu.edu

Dr. Ning Lu   North Carolina State University
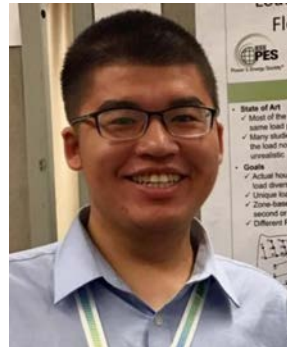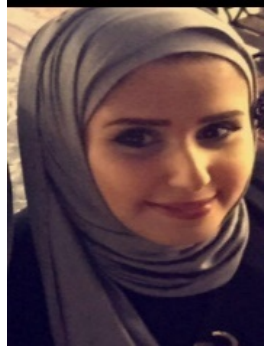
- GridWrx lab is currently the home of **15** PhD students
- We also host undergraduate researchers, master students, and visiting scholars to maintain a diversified group.
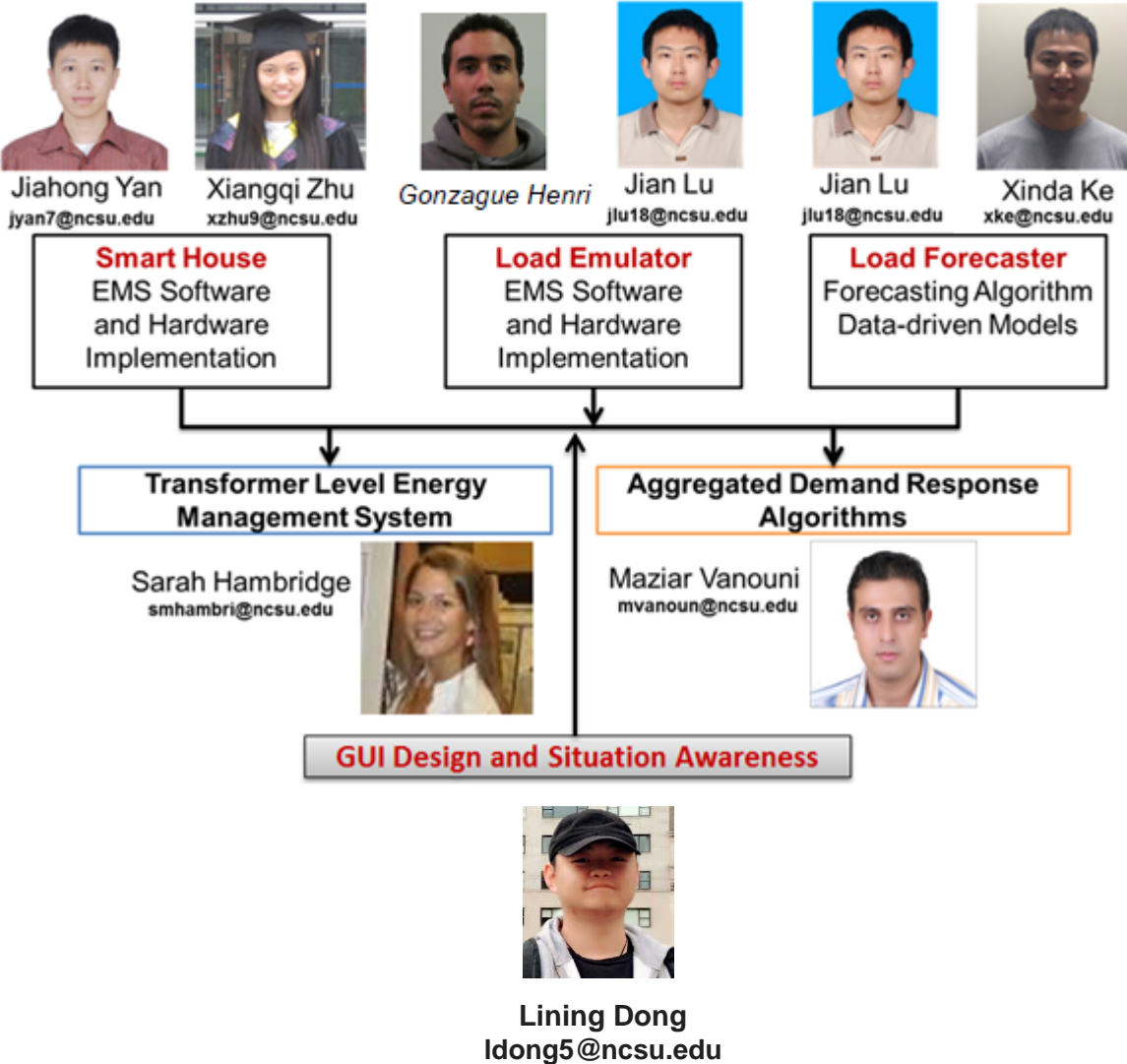
Dr. Ning Lu

North Carolina State University

GridWrx Lab
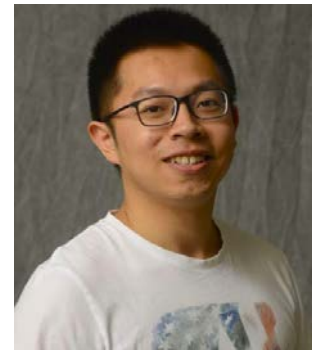
Microgrid, Home and Building Energy Management

Jiahong Yan
jyan7@ncsu.edu

Xiangqi Zhu
xzhu9@ncsu.edu

Gonzague Henri

Jian Lu
jlu18@ncsu.edu

Jian Lu
jlu18@ncsu.edu

Xinda Ke
xke@ncsu.edu

Smart House
EMS Software and Hardware Implementation

Load Emulator
EMS Software and Hardware Implementation

Load Forecaster
Forecasting Algorithm Data-driven Models

Transformer Level Energy Management System

Aggregated Demand Response Algorithms

Sarah Hambridge
smhambri@ncsu.edu

Maziar Vanouni
mvanoun@ncsu.edu

GUI Design and Situation Awareness

Lining Dong
ldong5@ncsu.edu

Dr. Ning Lu

Energy Storage, Renewable Integration, and Smart Planning

David Mulcahy
djmulcah@ncsu.edu

Weifeng Li
wli27@ncsu.edu

Xinda Ke
xke@ncsu.edu

Asmaa Alrushoud
aalrush@ncsu.edu

Caite McEntee
cmmcente@ncsu.edasu

Jiyu Wang
jwang49@ncsu.edu

Data Analytics

Yao Meng
ymeng3@ncsu.edu

Ming Liang
mliang3@ncsu.edu

Hardware-in-the-loop Test Systems

Fuhong Xie
fxie2@ncsu.edu

Mingzhi Zhang
mzhang33@ncsu.edu

North Carolina State University

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Part 1: Background

1. Li, Weifeng, Pengwei Du, and Ning Lu. "Design of a New Primary Frequency Control Market for Hosting Frequency Response Reserve Offers from both Generators and Loads." *IEEE Transactions on Smart Grid* (2017).
2. Xiangi Zhu, Jiahong Yan, and Ning Lu. "A Graphical Performance-based Energy Storage Capacity Sizing Method for High Solar Penetration Residential Feeders", IEEE trans. on Smart Grid, Volume: 8, Issue: 1, Jan. 2017.
3. Ke, X. D., Wu, D., Rice, J., Kintner-Meyer, M., & Lu, N. (2016). Quantifying impacts of heat waves on power grid operation. *Applied Energy*, *183*, 504-512.
4. X Ke, N Lu, and C Jin, "Control and Size Energy Storage for Managing Energy balance of Variable Generation Resources," IEEE Trans. on Sustainable Energy, vol. 6, No. 1, Jan. 2015.
5. N Lu and M Vanouni, "Passive energy storage using distributed electric loads with thermal storage," Journal of Modern Power Systems and Clean Energy, 2013, DOI 10.1007/s40565-013-0033-z.
6. C. Jin, N Lu, S. Lu, Y Makarov, and R.A. Dougal, "A Coordinating Algorithm for Dispatching Regulation Services Between Slow and Fast Power Regulating Resources," IEEE Trans. on Smart Grid, vol. 5, No. 2, March 2014.
7. N Lu, JH Chow, and AA Desrochers, "Pumped-Storage Hydro-Turbine Bidding Strategies in a Competitive Electricity Market." IEEE Trans. on Power Systems 19:834-842, 2004.
8. Jiyu Wang, Xiangqi Zhu, David Mulcahy, Catie McEntee, David Lubkeman, Ning Lu, Nader Samaan, Brant Werts, and Andrew Kling. "A Two-Step Load Disaggregation Algorithm for Quasi-Static Time-Series Analysis on Actual Distribution Feeders," accepted by the 2018 IEEE Power & Energy Society General Meeting, Portland, OR, 2018.
9. Fuhong Xie, N. Lu, and Jiahong Yan, "Design of a Mobile Energy Management Unit for Off-grid Mini-microgrids," accepted by Proc. of 2018 IEEE Power & Energy Society General Meeting, Portland, OR, 2018.
10. G. Henri and N. Lu, "A Multi-Agent Shared Machine Learning Approach for Real-time Battery Operation Mode rediction and Control," Accepted by Proc. of 2018 IEEE Power & Energy Society General Meeting, Portland, OR, 2018.
11. G. Henri, N. Lu, and C. Carrejo, "A Machine Learning Approach for Real-time Battery Optimal Operation Mode Prediction and Control", Proc. of IEEE/PES Transmission and Distribution Conference and Exposition, 2018.
12. G. Henri, N. Lu, and C. Carrejo, "Design of a Novel Mode-based Energy Storage Controller for Residential PV Systems." Proc. of 2017 Power & Energy Society ISGT Europe Conference, Turino, 2017. (can be downloaded at the the link provided below)
13. Xiangqi Zhu, Gonzague Henri, Jiahong Yan, and N. Lu. "A Cost-Benefit Study of Sizing Residential PV and ES Systems based on Synthesized Load Profiles", Proc. of 2017 IEEE Power & Energy Society General Meeting, Chicago, IL, 2017.

For more reference for the paper we published in the area of energy storage please visit my website.

Dr. Ning Lu   North Carolina State University

1. N Lu, YV Makarov, and MR Weimar. 2010. *The Wide-area Energy Storage and Management System Phase 2 Final Report.* PNNL-19720. Pacific Northwest National Laboratory, Richland, Washington.

2. N Lu, YV Makarov, MR Weimar, F Frank, S. Murthy, J. Arseneaux, C. Loutan, and S Chowdhury. 2010. *The Wide-area Energy Storage and Management System (Phase 2): Interim Report (2) – Flywheel Field Tests.* PNNL-19669, Pacific Northwest National Laboratory, Richland, Washington.

3. Chunlian Jin, Ning Lu, Shuai Lu, Yuri Makarov, Roger A. Dougal, 2010. "Novel Dispatch Algorithm for Regulation Service using a Hybrid Energy Storage System" *Proc. of the 2011 IEEE PES General Meeting*, Detroit, Michigan, USA.

4. Chunlian Jin, Shuai Lu, Ning Lu, Roger A. Dougal. 2010. "Cross-Market Optimization for Hybrid Energy Storage Systems," *Proc. of the 2011 IEEE PES General Meeting*, Detroit, Michigan, USA.

5. N Lu, MR Weimar, YV Makarov, and C Loutan. 2010. "An Evaluation of the NaS Battery Storage Potential for Providing Regulation Service in California." *Proc. of the 2011 IEEE PSCE*, Phoenix, Arizona.

8. N Lu, MR Weimar, YV Makarov, FJ Rudolph, SN Murthy, J Arseneaux, and C Loutan. 2010. "An Evaluation of the Flywheel Potential for Providing Regulation Service in California." In: *Proc. of the 2010 IEEE PES General Meeting*, Minneapolis, Minnesota.

9. S Lu, YV Makarov, Y Zhu, N Lu, K Prakash, C Nirupama, and B Bhujanga. 2010. "Unit Commitment Considering Generation Flexibility and Environmental Constraints." In: *Proc. of the 2010 IEEE PES General Meeting*, Minneapolis, Minnesota.

10. B. Yang, Y. Makarov, J. DeSteese, V. Viswanathan, P. Nyeng, B. McManus and J. Pease, "On the Use of Energy Storage Technologies for Regulation Services in Electric Power Systems with Significant Penetration of Wind Energy", Proc. 5th Int. Conf. on the European Electricity Market, Lisbon, Portugal, May 28-30, 2008.

11. P. Nyeng, B. Yang, J. Ma, Y.V. Makarov, J. H. Pease, D. Hawkins and C. Loutan, "Coordinated multi-objective control of regulating resources in multi-area power systems with large penetration of wind power generation", Proc. 7th Int. Workshop on Large-Scale Integration of Wind Power into Power Systems, Madrid, Spain, May 26-27, 2008.

12. Y.V. Makarov, B. Yang, J.G. DeSteese, P. Nyeng, C.H. Miller, J. Ma, S. Lu, V.V. Viswanathan, D.J. Hammerstrom, B. McManus, J. H. Pease, C. Loutan and G. Rosenblum "Wide-Area Energy Storage and Management System to Balance Intermittent Resources in the Bonneville Power Administration and California ISO Control Areas," Proc. 8th Int. Workshop on Large-Scale Integration of Wind Power into Power Systems, Bremen, Germany, Oct. 14-15, 2009.

13. Y.V. Makarov, P. Nyeng, B. Yang, J. Ma, J.G. DeSteese, D.J. Hammerstrom, S. Lu, V.V. Viswanathan, and C.H. Miller, Wide-Area Energy Storage and Management System to Balance Intermittent Resources in the Bonneville Power Administration and California ISO Control Areas. PNNL-17574. Pacific Northwest National Laboratory, Richland, WA, 2008.

- Superconducting magnetic energy storage (SMES)
- Super capacitors
- Pumped-hydro power plants (PHP)
- Compressed air energy storage (CAES)
- Flywheels
- Batteries
  - NaS (sodium-sulfur), Li-ion, lead acid, flow batteries, etc.
  - Electric vehicles
- Thermal energy storage devices
  - Ice storage, water heaters, air conditioning units, etc.
  - Demand response programs using load with thermal storage capabilities

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Direct Storage

Electrical charges:
Capacitors
SEMS

Indirect Storage

(via 1-way or 2-way energy conversion)

Potential	Kinetic	Chemical	Thermal
Pumped hydro compress air	Flywheel	Batteries	Water heaters, air conditioners

Time
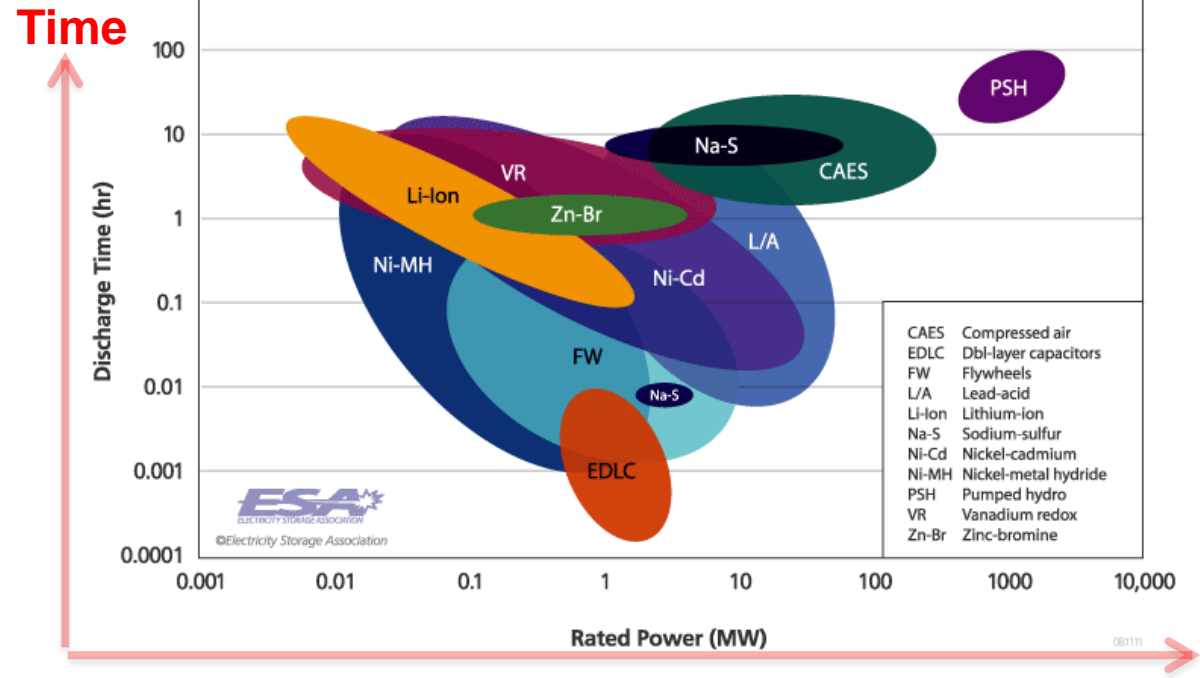
One-directional
energy conversion

Reference: Yang, et al., *Chemical Reviews*, 111, 3577, 2011

Power

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▶ Traditional (Energy Markets)
- Backup
- Peak shaving
- Energy shifting
- Arbitrage

▶ Advanced (Ancillary Services)
- Regulation
- Load following service
- Frequency response
- Spinning/non-spinning reserves
- Reactive power support

▶ Traditional (Energy Markets)

- ○ Backup
- ○ Peak shaving
- ○ Energy shifting
- ○ Arbitrage

▶ Advanced (Ancillary Services)

- ○ Regulation
- ○ **Load following service**
- ○ **Frequency response**
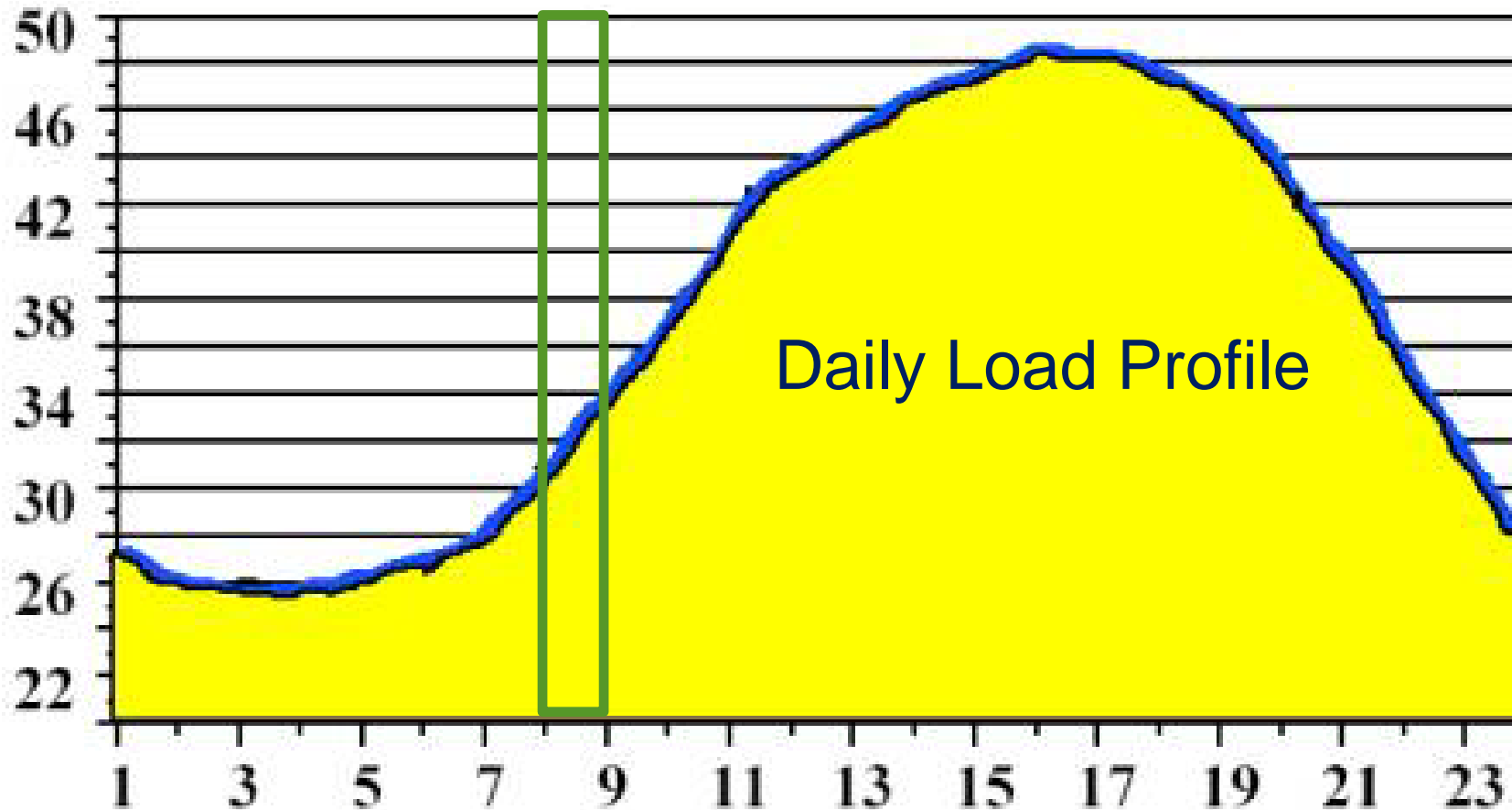- ○ Spinning/non-spinning reserves
- ○ Reactive power support

Part 2: Regulation Services

1. Yao Meng, Ming Liang, Ning Lu, "A Cost Benefit Study of using Energy Storage to Provide Frequency Regulation" Submitted to 2019 IEEE ISGT conference.
2. N Lu, YV Makarov, and MR Weimar. 2010. *The Wide-area Energy Storage and Management System Phase 2 Final Report*. PNNL-19720. Pacific Northwest National Laboratory, Richland, Washington.
3. N Lu, YV Makarov, MR Weimar, F Frank, S. Murthy, J. Arseneaux, C. Loutan, and S Chowdhury. 2010. *The Wide-area Energy Storage and Management System (Phase 2): Interim Report (2) – Flywheel Field Tests*. PNNL-19669, Pacific Northwest National Laboratory, Richland, Washington.
4. Chunlian Jin, Ning Lu, Shuai Lu, Yuri Makarov, Roger A. Dougal, 2010. "Novel Dispatch Algorithm for Regulation Service using a Hybrid Energy Storage System" *Proc. of the 2011 IEEE PES General Meeting*, Detroit, Michigan, USA.
5. Chunlian Jin, Shuai Lu, Ning Lu, Roger A. Dougal. 2010. "Cross-Market Optimization for Hybrid Energy Storage Systems," *Proc. of the 2011 IEEE PES General Meeting*, Detroit, Michigan, USA.
6. N Lu, MR Weimar, YV Makarov, and C Loutan. 2010. "An Evaluation of the NaS Battery Storage Potential for Providing Regulation Service in California." *Proc. of the 2011 IEEE PSCE*, Phoenix, Arizona.
7. N Lu, MR Weimar, YV Makarov, FJ Rudolph, SN Murthy, J Arseneaux, and C Loutan. 2010. "An Evaluation of the Flywheel Potential for Providing Regulation Service in California." In: *Proc. of the 2010 IEEE PES General Meeting*, Minneapolis, Minnesota.

Intra-hour Applications

Daily Load Profile

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Balance the mismatches between the load forecast and the actual load

Load following

Economic Dispatch

10-minute load forecast

Decremental Energy

Incremental Energy

Regulation

Calculated by AGC

Hourly-ahead Load Forecast

Actual Load

Hour 8

Hour 9

Figure by Craig Taylor and Don DeBerry, presented at 2002 OSIsoft T&D Users Conference

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- **Regulation services:** balances generation and load in real-time to maintain system frequency and tie-line power flows at the scheduled values.

- **Inputs:** Area Control Error(ACE) and Tie-line Flow Deviations.

- **Signal resolution:** 2-10 seconds

- **Characteristics:** mostly energy neutral, random in magnitude (very hard to forecast)

NY-ISO ACE signal of June,2017 and its probability density function

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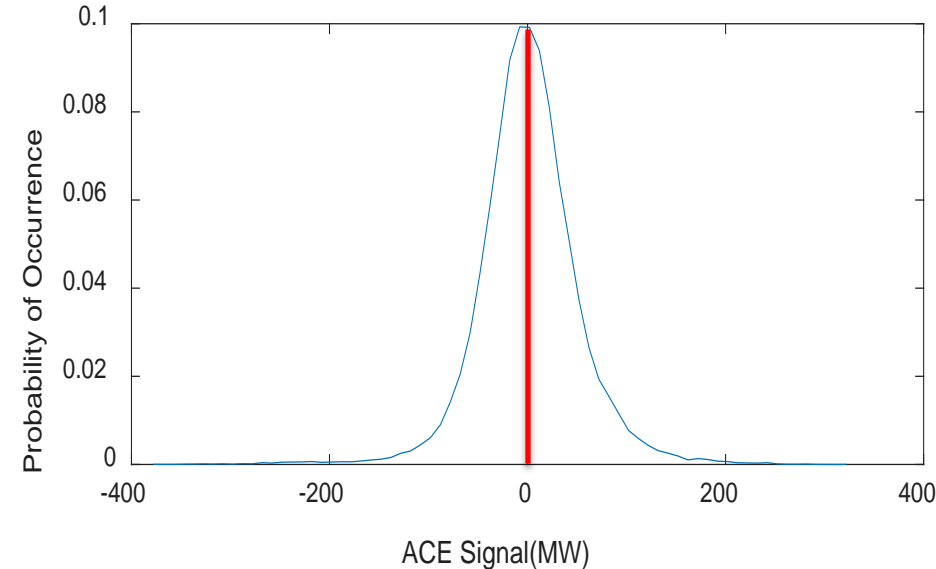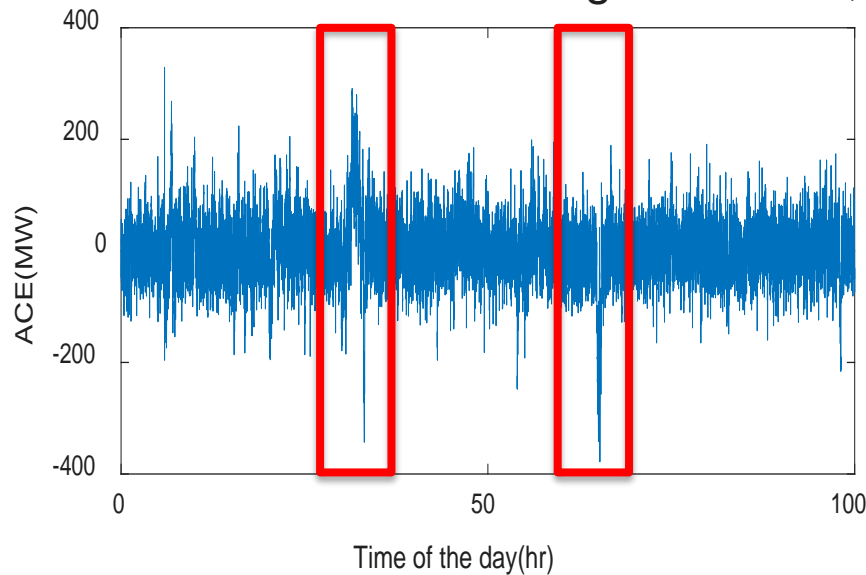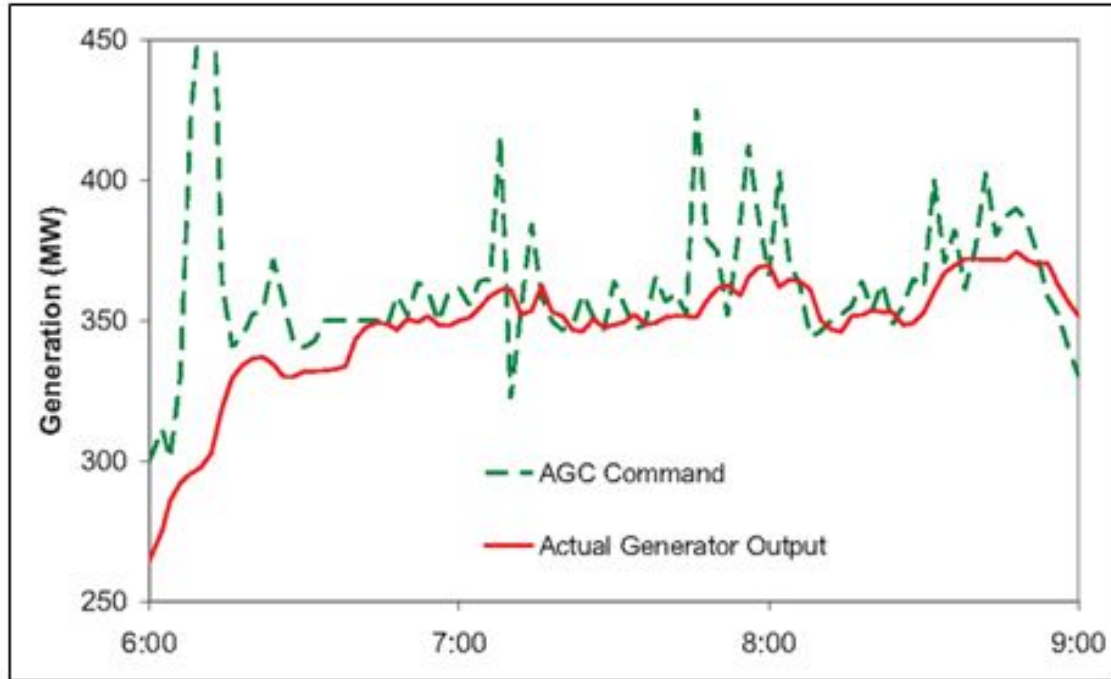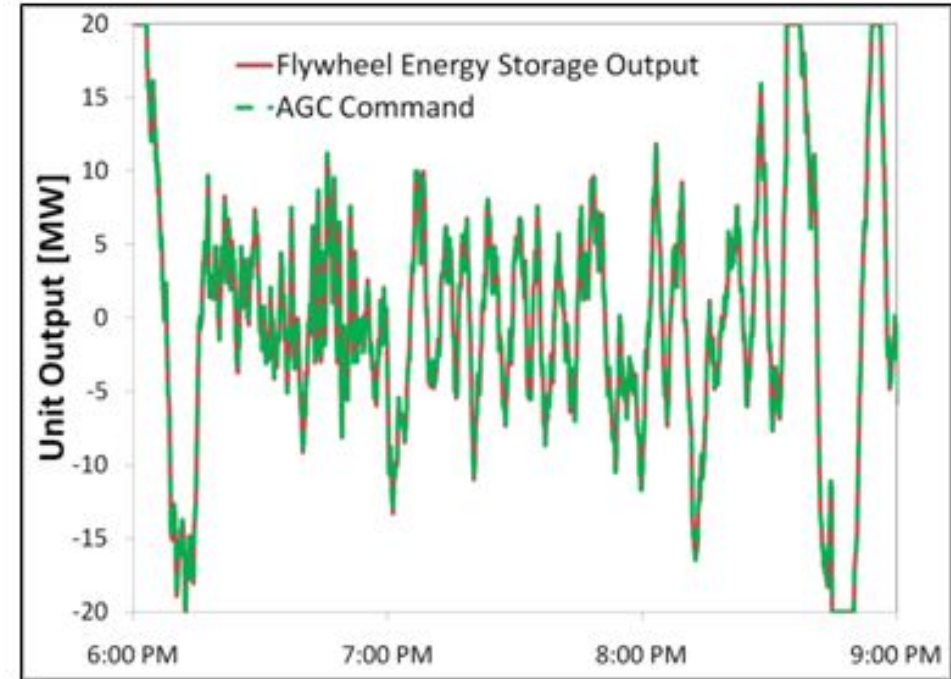
Slow ramping Generator vs. Advanced Energy Storage

Advantages	1. Reduce the wear-and-tear of the traditional generators
	2. Reduce the amount of required regulation capacity
	3. Improve the quality of regulation services

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- Energy storage systems have energy limits.
  - When regulation signals have significant DC components, energy storage devices will soon be fully charged/discharged
- Three approaches to deal with this issue
  - **Design energy-neutral frequency regulation signal**
  - **Design operation strategy** to maintain the state-of-charge (SOC) levels
  - Allow storage to adjust its committed regulation services in a shorter interval
- The first method has been implemented by PJM and ISO-NE.
  - **Fast regulation signal:** Applying a high-pass filter to the AGC signal.
 - Signals with **a fast ramping rate** but **energy neutral**.

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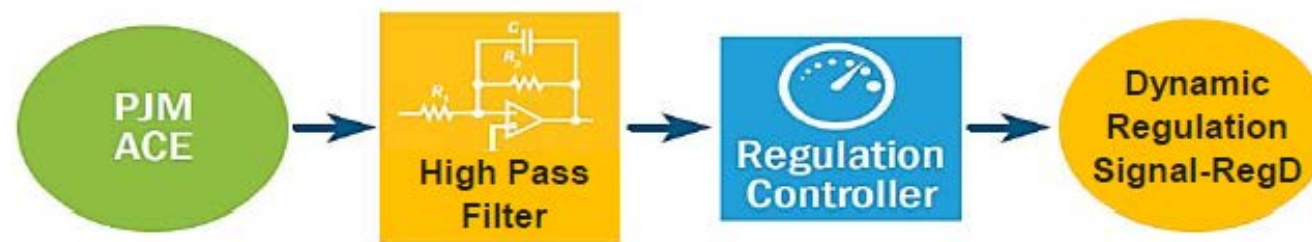
**Monetary Incentives: FERC Order 755** requires the implementation of **pay-for-performance** regulation market

Design Considerations: FERC Order 784 requires the **improvement of signal design** considering the state of charge constraint of energy storage system
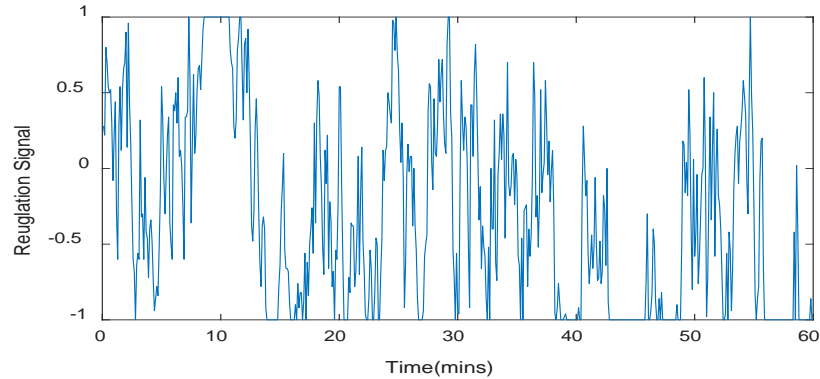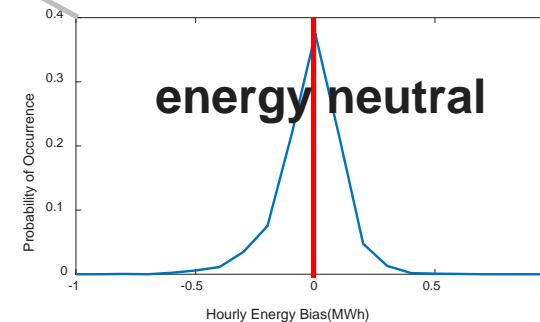

One hour NY-ISO regulation signal
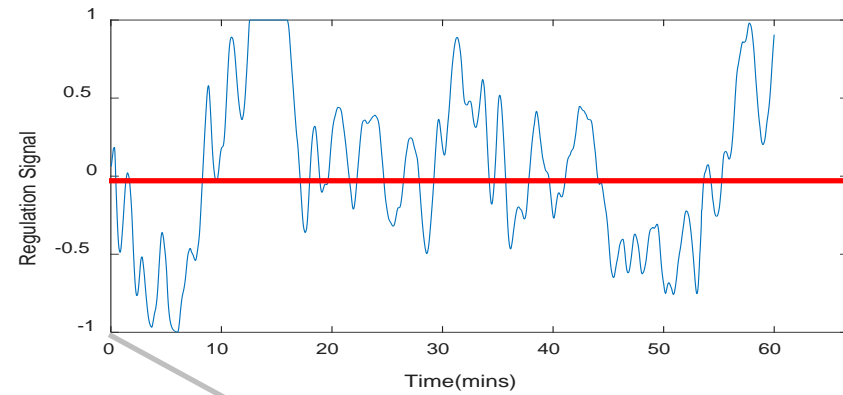
One hour PJM RegD signal

PDF of PJM RegA

energy neutral

PDF of PJM RegD

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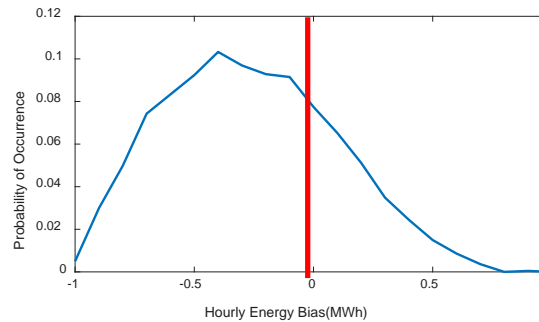
Regulation capacity: participating resource will be rewarded by the bidding capacity P_{bid}^{reg}, unit: \$/MWh. Regulation-up and regulation down signals have the same power limit except in the CASIO control area

Regulation mileage M: the sum of the absolute values of the regulation control signal movements, unit \$/ΔMW, P_t^{reg} is the power output of a regulation unit at t

$$M = \sum_{0}^{T} \frac{\left|P_t^{reg} - P_{t-1}^{reg}\right|}{P_{bid}^{reg}}$$
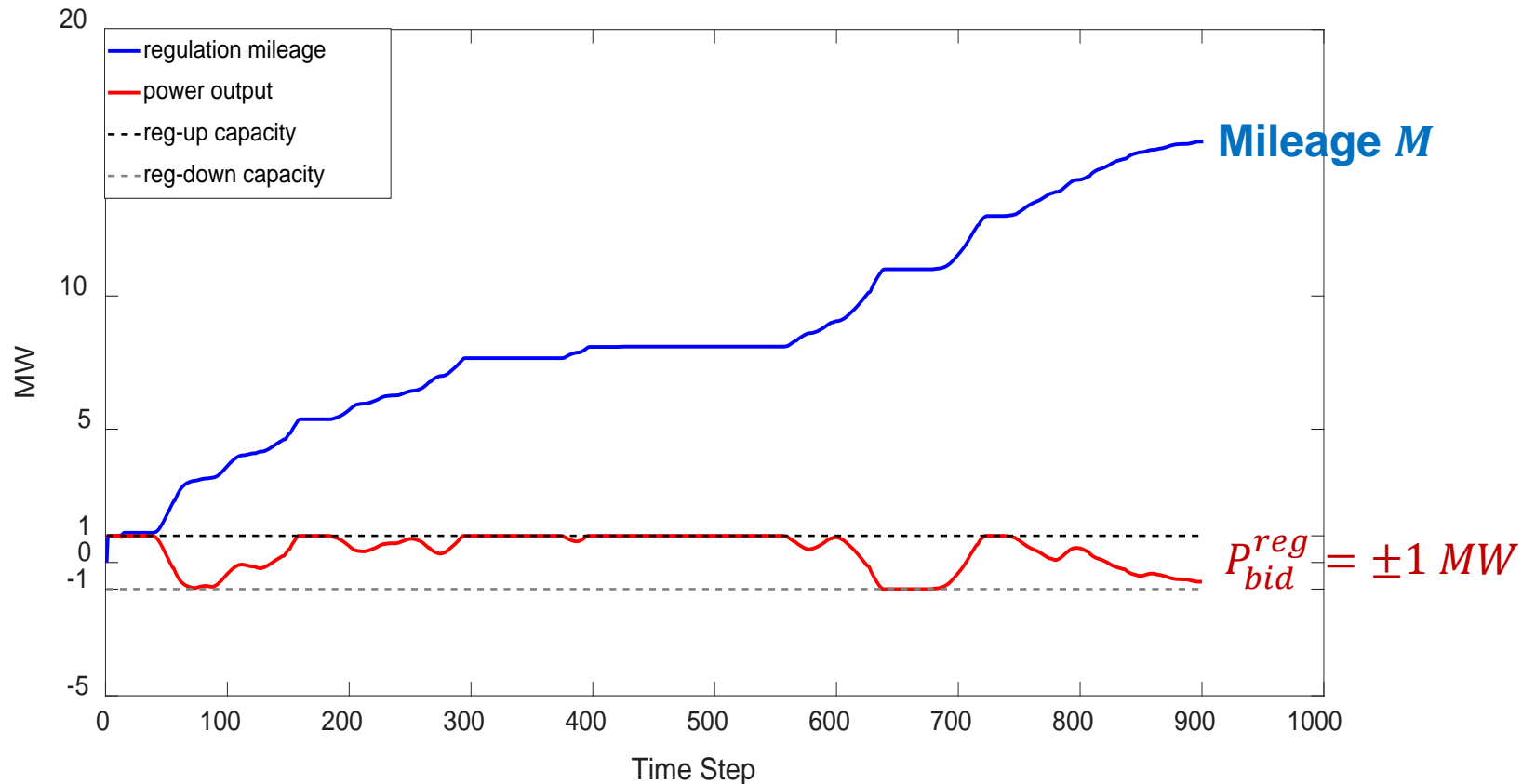
Performance factor λ: A value between 0 and 1, represent the response accuracy with respect to the regulation instructions. A general penalization format is as follows:

$$\text{Payment} = P_{bid}^{reg}(\rho_c + \boldsymbol{\lambda}M\rho_M)$$

where ρ_c, ρ_M are capacity clearing price and mileage clearing price, respectively. In this analysis, we assume $\lambda = 1$.

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$$\text{Payment} = \textcolor{red}{\boldsymbol{P_{bid}^{reg}}}(\rho_c + \textcolor{red}{\boldsymbol{\lambda M}}\rho_M)$$

$$M = \sum_0^T \frac{\left|P_t^{reg} - P_{t-1}^{reg}\right|}{P_{bid}^{reg}}$$

Mileage M

$P_{bid}^{reg} = \pm 1\ MW$

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Energy Storage Models

$$E_t - E_{t-1} = \Delta t \eta_c P_t^{RegDown} - \Delta t \eta_d P_t^{RegUp} - \Delta t P_t^{SelfDisc}$$

Discharged energy   Charging energy   Self-discharged energy

$$0 \leq P_t^{RegDown} \leq P_{bid}^{reg}$$

$$0 \leq -P_t^{RegUp} \leq P_{bid}^{reg}$$

$$E^{Lowerlim} \leq E_t \leq E^{Upperlim}$$

Modeling Parameters

ESS Technology		Lithium-ion	Flywheel
charging efficiency	η_c	0.85	0.95
discharging efficiency	η_d	1	0.95
self-discharging rate	$P_t^{SelfDisc}$	2-4% per month	2% per month

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- Start-up nor shut-down costs are not considered
- Actual annual revenue for year 2017 is calculated and we assume that the same revenue is received over the entire lifetime.
- Revenue includes two payments: mileages and capacity
- Cost includes installation and O&M cost
- NPV (Net Present Value) is calculated assuming the discount rate is 10%

Revenue

$$R = R_{mileage} + R_{capacity}$$

Cost-of-service

$$C = C_{install} + C_{O\&M}$$

Net Present Value

$$NPV = \sum_{i=1}^{N} \frac{V(i)}{(1+r)^i}$$

$$\boldsymbol{Profit} = NPV_{revenue} - NPV_{cost}$$

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- Lifetime of a battery storage system can be estimated based on how many charging/discharging cycles it has completed at different depth of discharge(DOD)
- Rain-flow algorithm is used for estimating battery lifetime depreciation
- The flywheel lifetime is assumed to be constant

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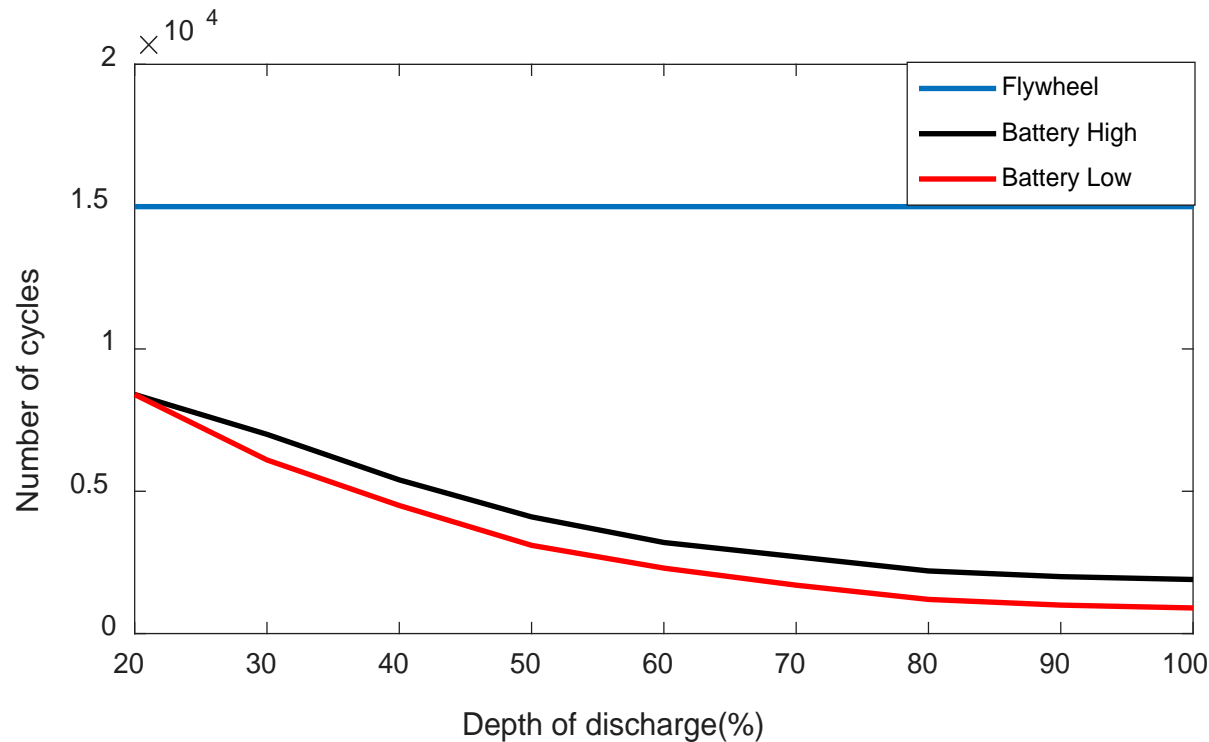
One directional service: Energy storage system only takes "up" signal when discharging, while only taking "down" signal when charging
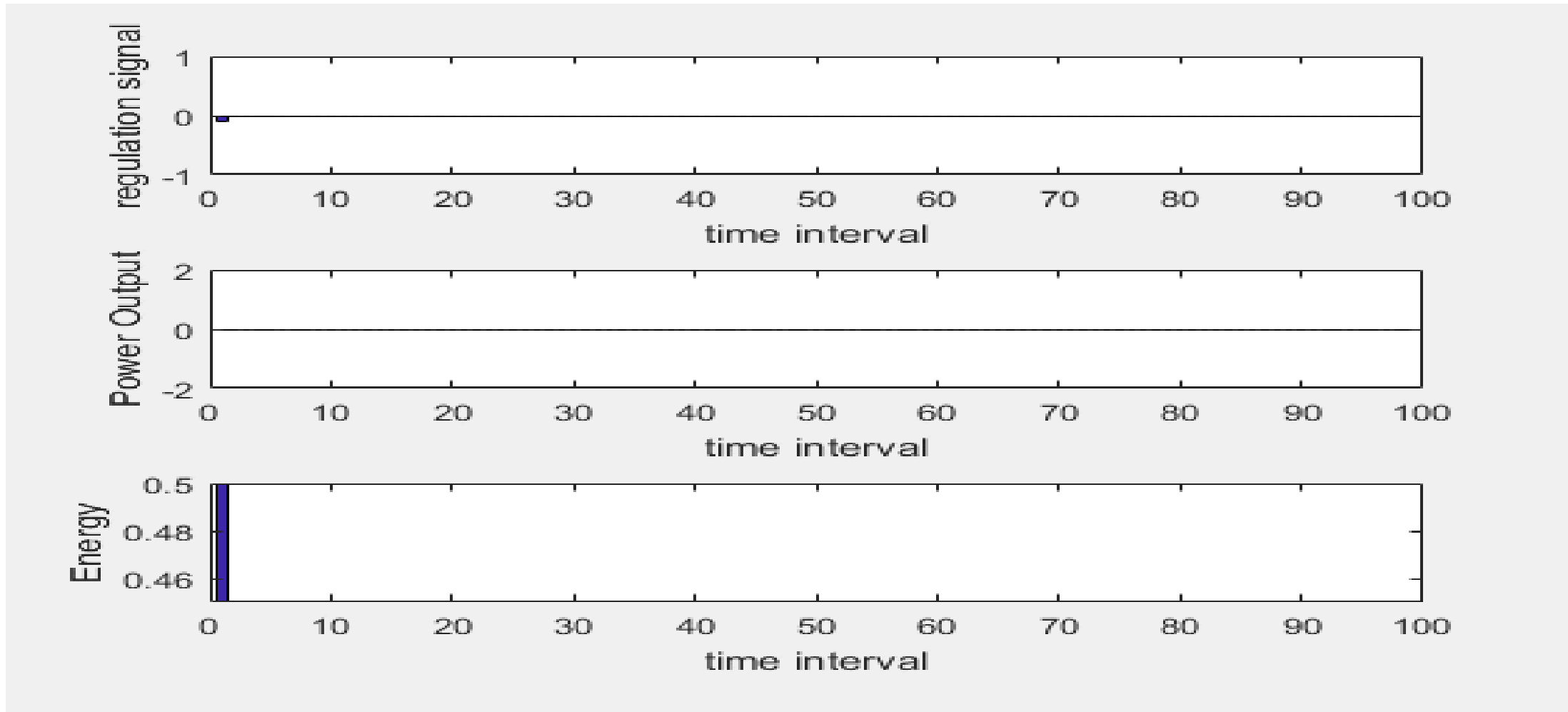
Two directional service: Energy storage system can take both "up" and "down" signal when possible.

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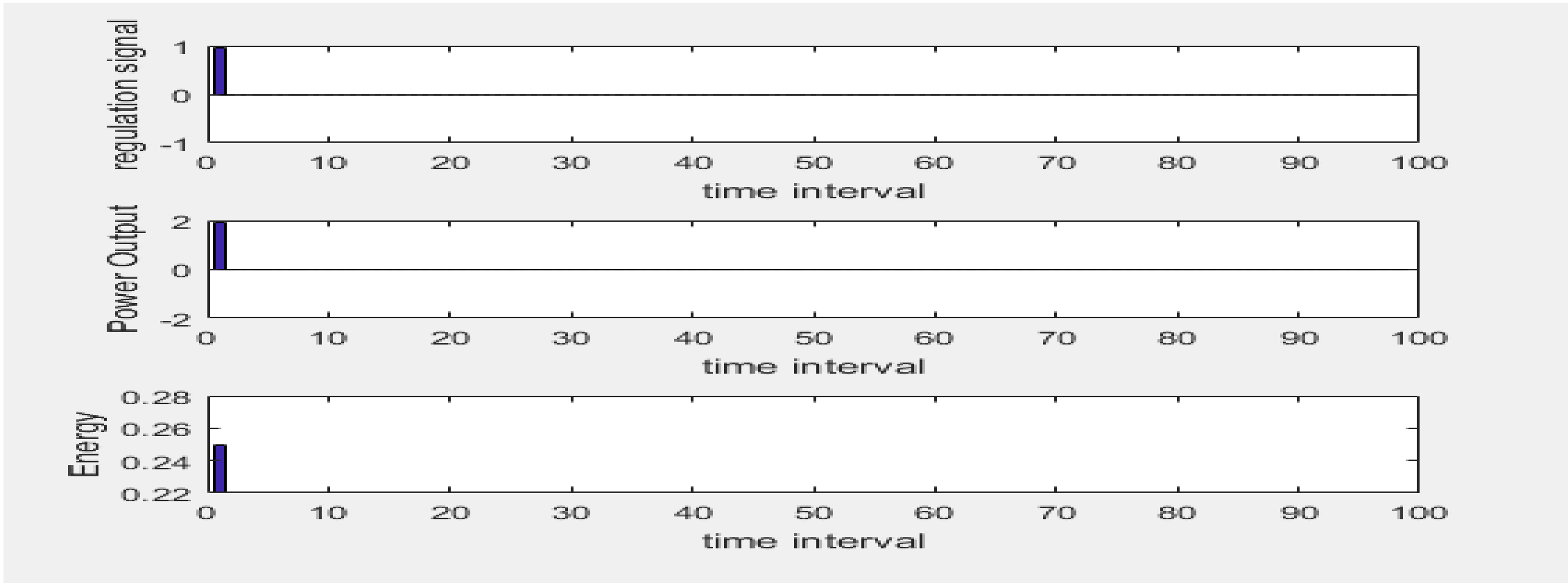
To evaluate the accuracy of following regulation signals, we calculated **response rate** as:

$$RR = \frac{n_{fulfilled}}{n_{total}} \times 100\%$$

where $n_{fulfilled}$ is the number of regulation signals fully following by the ESS and n_{total} is the total number of regulation signals.

To evaluate the lifetime depreciation when providing regulation services, we calculated the **aging ratio** as:

$$A = \frac{L_{default} - L_{remain}}{L_{default}} \times 100\%$$

where $L_{default}$ is the default lifetime of battery, L_{remain} is the remaining lifetime after certain period of service estimated by rain-flow algorithm.

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- Regulation signals and the corresponding price data were downloaded from PJM and NY-ISO website, the data was collected from January 1, 2017 to December 31, 2017

- Designed lifetime of Li-ion battery is 10 years, while the designed lifetime of flywheel is 21 years

- The power and energy rating of Li-ion battery and flywheel is 1MW and 0.5 MWh, respectively

- Cost Parameters

	Li-ion(0.5hr)	Li-ion(2hr)	Li-ion(4hr)	Flywheel
Current Cost($/kWh)	1650	725	525	4538.32
2030 Cost ($/kWh)	629	276	200	-
O&M($/Kw-yr)	10	10	10	7

Technology advancement

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Part 4: Cost-benefit Study Results

|		PJM RegD		PJM RegA		NY-ISO	
		1-direction	2-direction	1-direction	2-direction	1-direction	2-direction
Battery	Mileage (ΔMW/MW)	133470	263210	20101	35472	87562	156450
	Response Rate(%)	**99.94**	**95.05**	99.91	55.7	99.92	85.46
	Estimate Lifetime(yrs)	4.72	3.89	5.93	4.23	5.28	3.99
Flywheel	Mileage (ΔMW/MW)	133810	294480	20291	43100	87140	159290
	Response Rate(%)	**99.94**	**94.93**	99.90	59.12	99.92	86.26
	Estimate Lifetime(yrs)	21	21	21	21	21	21

1. Regulation **signal design** makes a significant difference.
2. When providing regulation services, **battery lifetimes are shortened**.
3. When providing RegD services, battery lifetimes can be further shortened but not by much.
4. When providing 1-directional services, battery lifetimes can be prolonged.
5. As the flywheel can cycle as many times at low DOD as at high DODs, its lifetime is not affected by providing the regulation services.
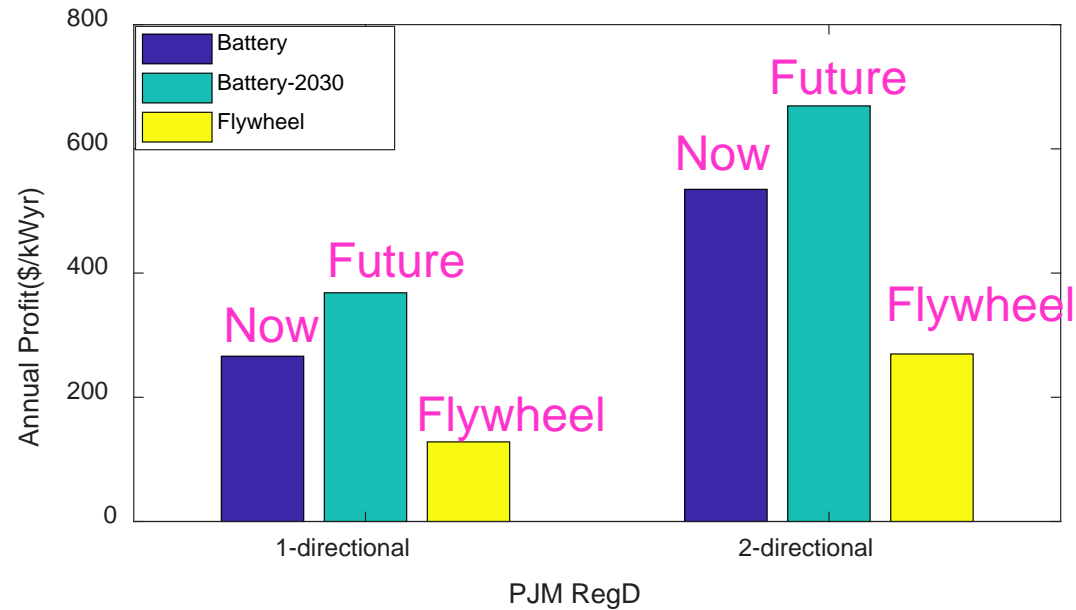
Dr. Ning Lu   North Carolina State University
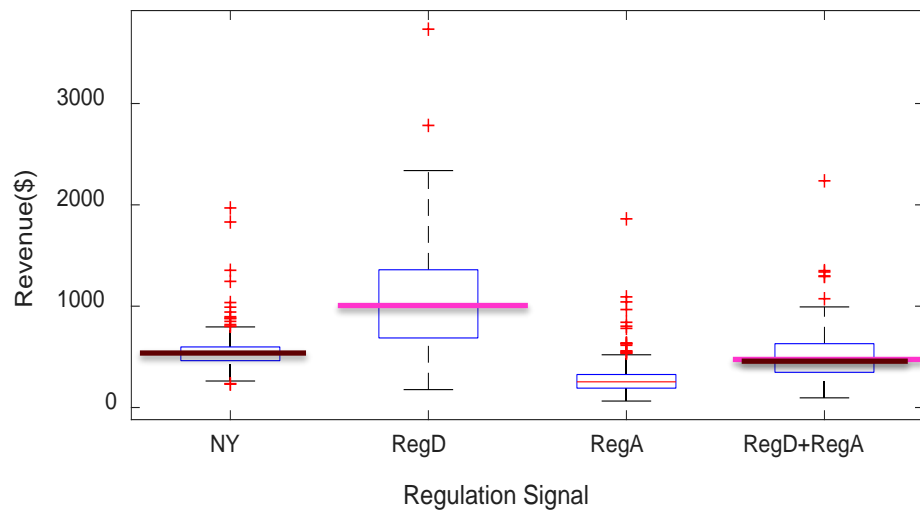
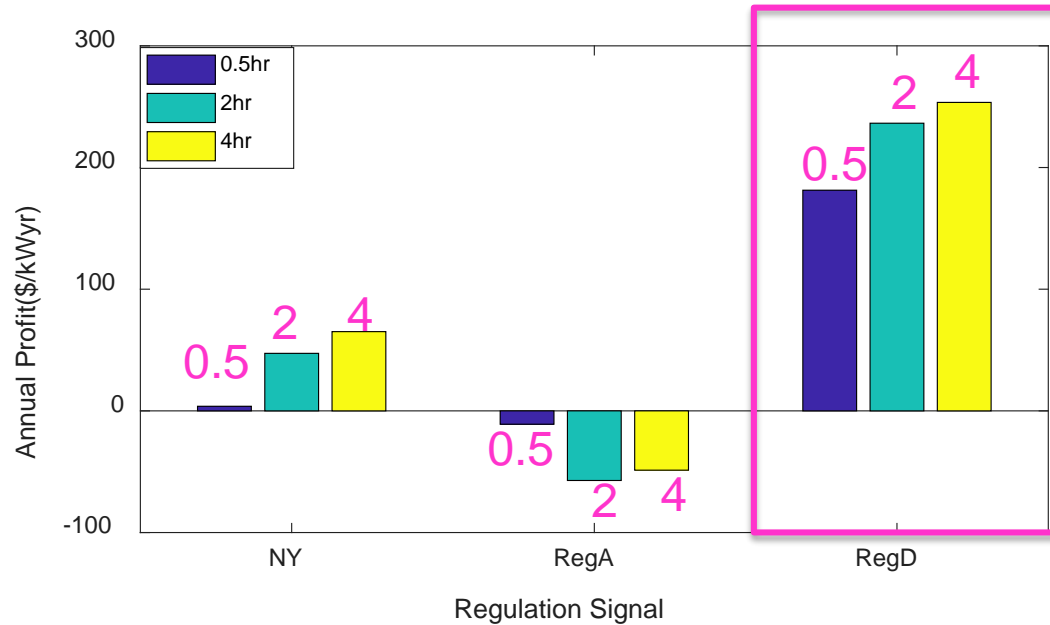**Comparison of daily revenue**
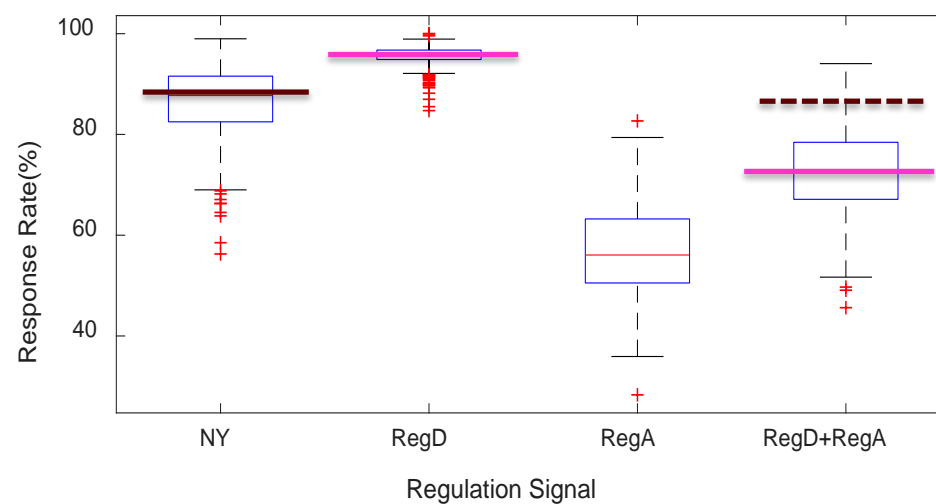
Comparison of daily response rate
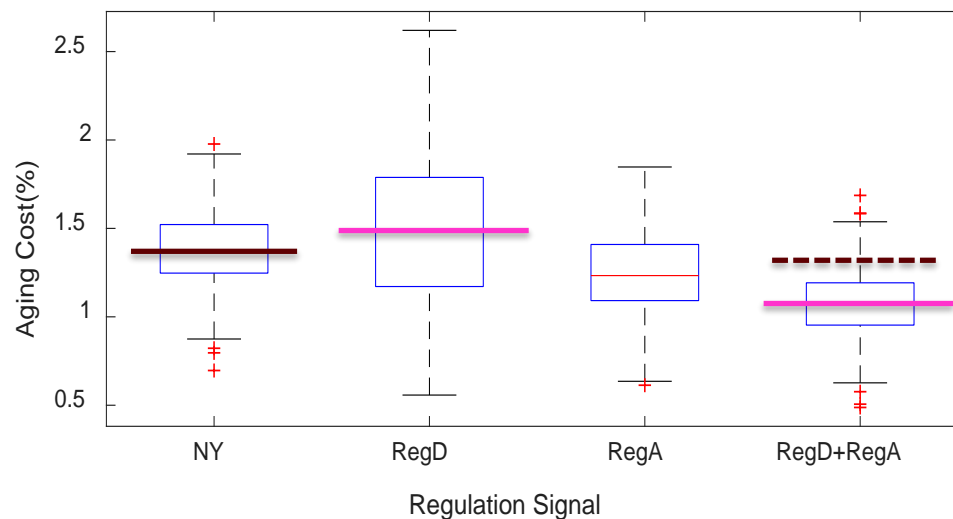
Comparison of lifetime depreciate

Profits comparison of different ESS technologies

Profits comparison of different battery sizes

A larger size battery has a longer service life. When supplying RegD, the service life are 3.8, 5.5, 13.5 years for 0.5, 2 and 4 hours battery, respectively.

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- # We have finished the following comparisons
  - Regular regulation signals **v.s.** storage-friendly signals
  - 1-directional **v.s.** 2-directional services
  - Regional differences (PJM **v.s.** NYISO)
  - Different battery sizes
  - energy storage technologies (Li-ion Battery **v.s.** Flywheel; lifetime sensitive to DOD **v.s.** lifetime not sensitive to DOD)

- # What to come
  - Market-based **v.s.** non-market based regulation services
    - Need signals from non-market based systems
  - Different energy storage control algorithms
    - Optimize energy storage operation
    - Stack the regulation service with other type of services

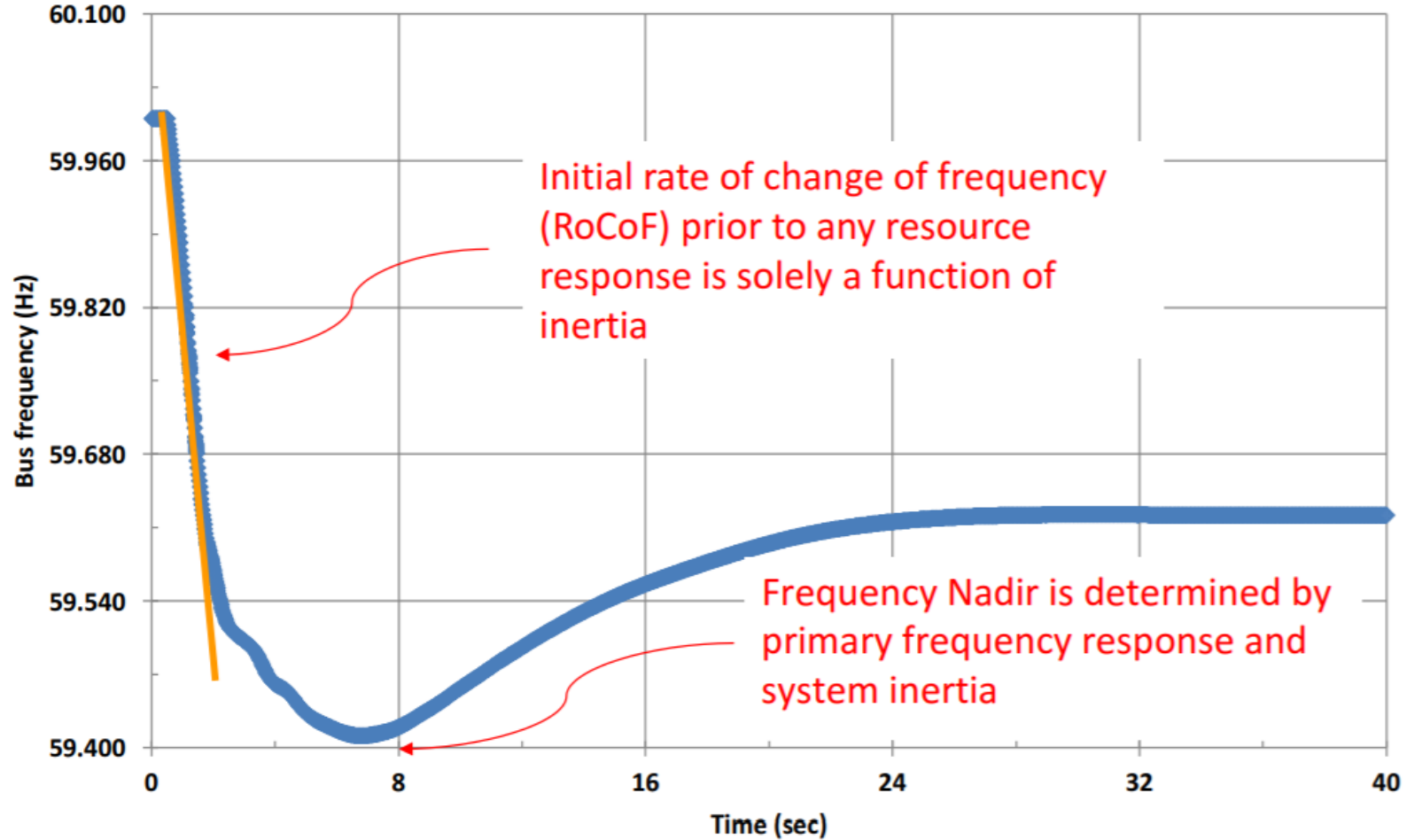Dr. Ning Lu   North Carolina State University

Part 5: Fast Frequency Response Services

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Li, Weifeng, Pengwei Du, and Ning Lu. "Design of a New Primary Frequency Control Market for Hosting Frequency Response Reserve Offers from both Generators and Loads." *IEEE Transactions on Smart Grid* (2017).

Loss of 2750 MW Generation

Initial rate of change of frequency (RoCoF) prior to any resource response is solely a function of inertia

Frequency Nadir is determined by primary frequency response and system inertia

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Actual System Response
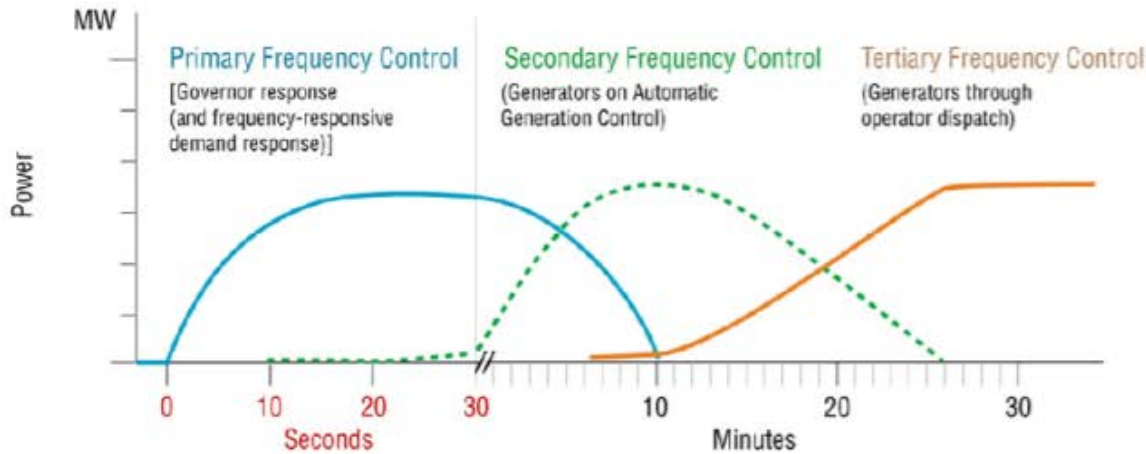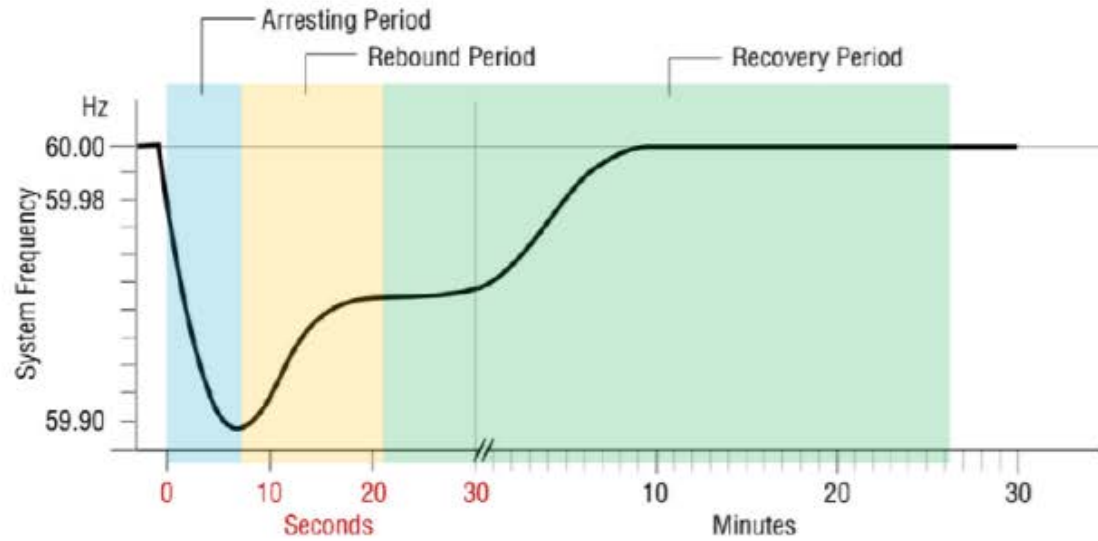
System response

frequency

Primary frequency response is the only control action that can oppose the free-fall of frequency within seconds before involuntary load shedding takes place.

Loss of 2750 MW Generation

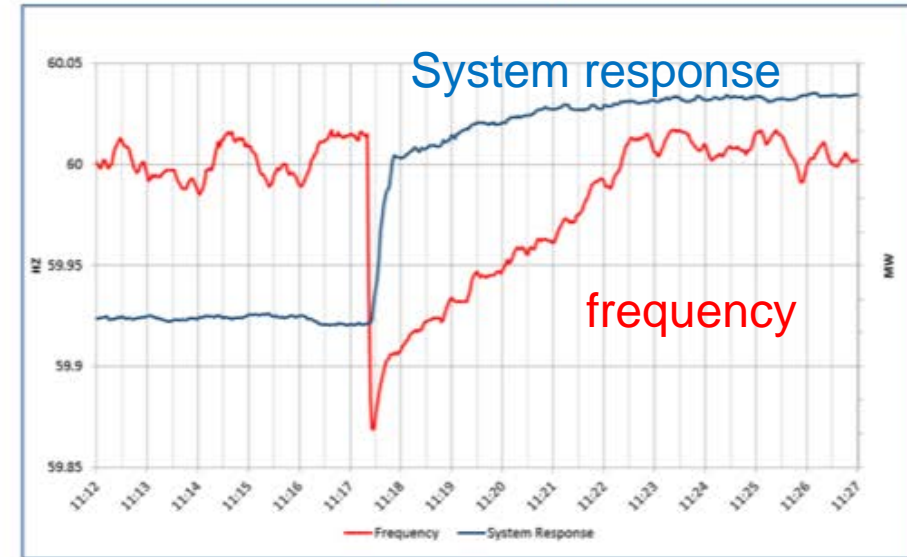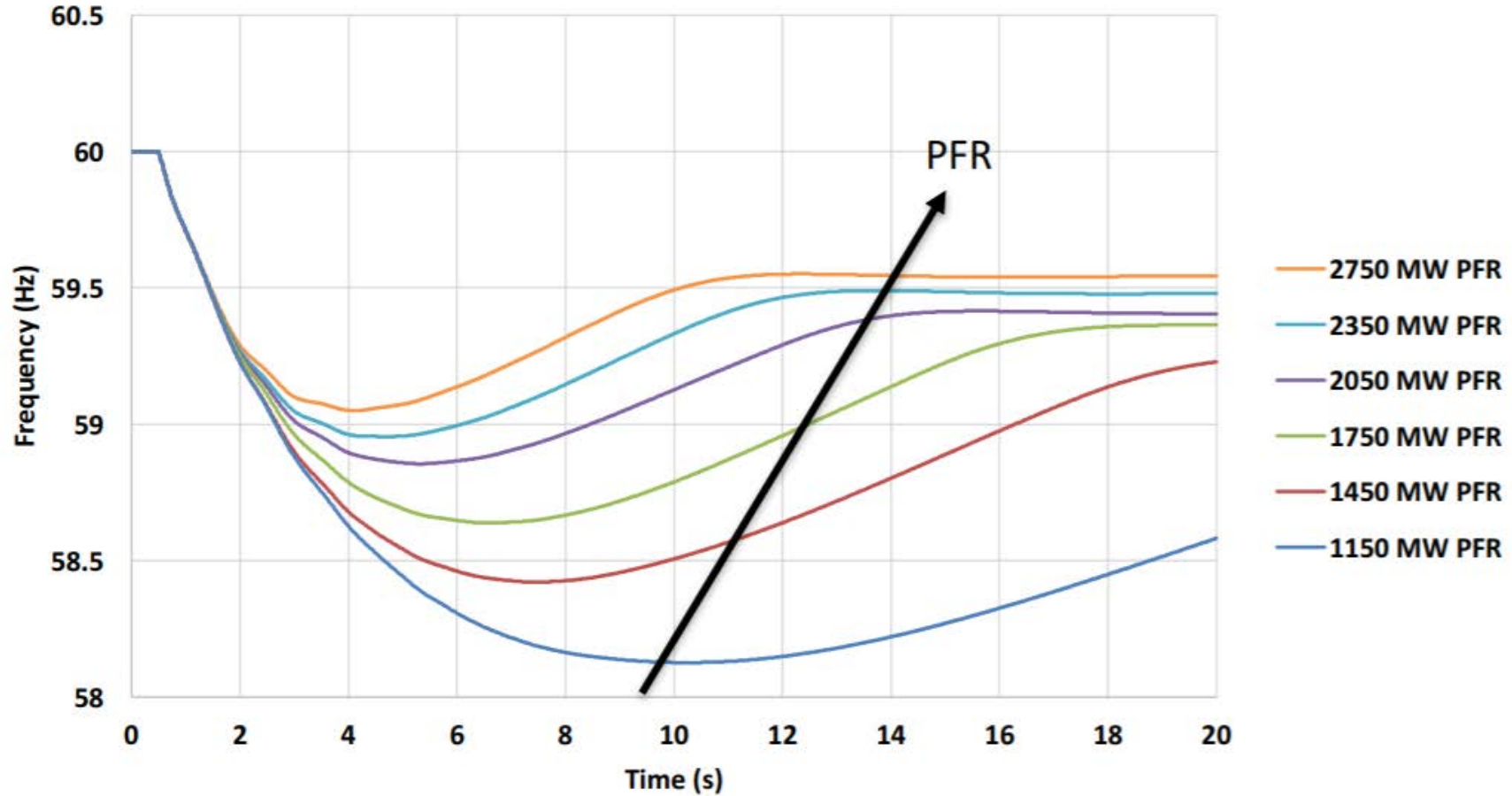More primary frequency response → less frequency drops and faster recovery

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Inertia reflects a synchronous machine's physical character to slow down the rate of frequency change.

$$\frac{d\Delta f}{dt} = \frac{f_0}{2HS_B}(\Delta P_m - \Delta P_e)$$

← Inertia

f: Rotating frequency of the machine, H: Inertia constant of the synchronous machine
S_B: Rated power of the generator, ΔP_m: Change in mechanical power
ΔP_e: Change in electric power demand
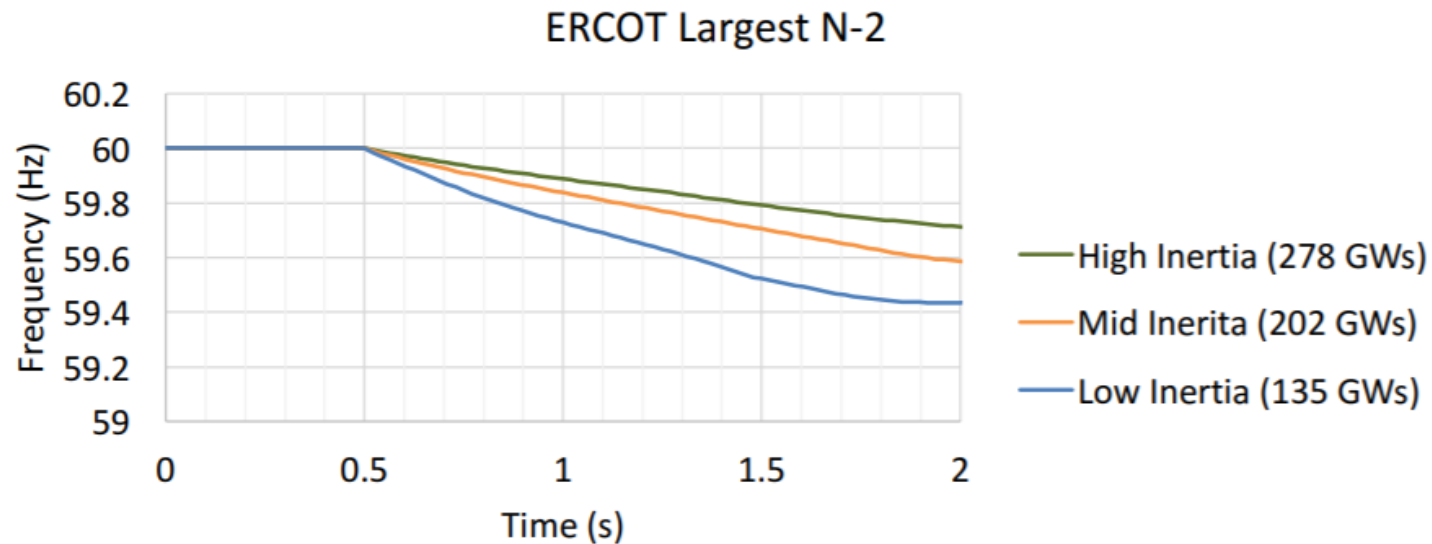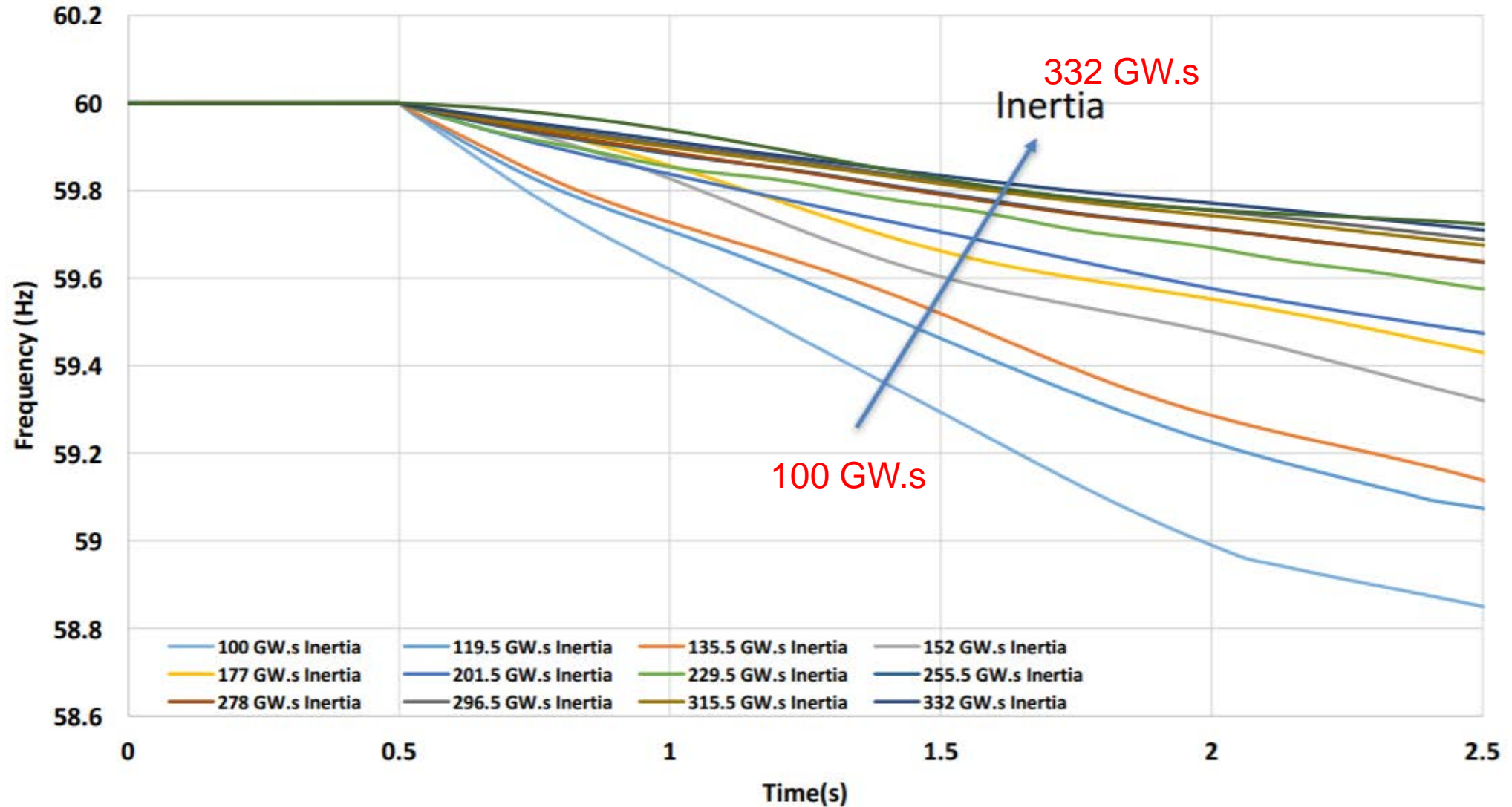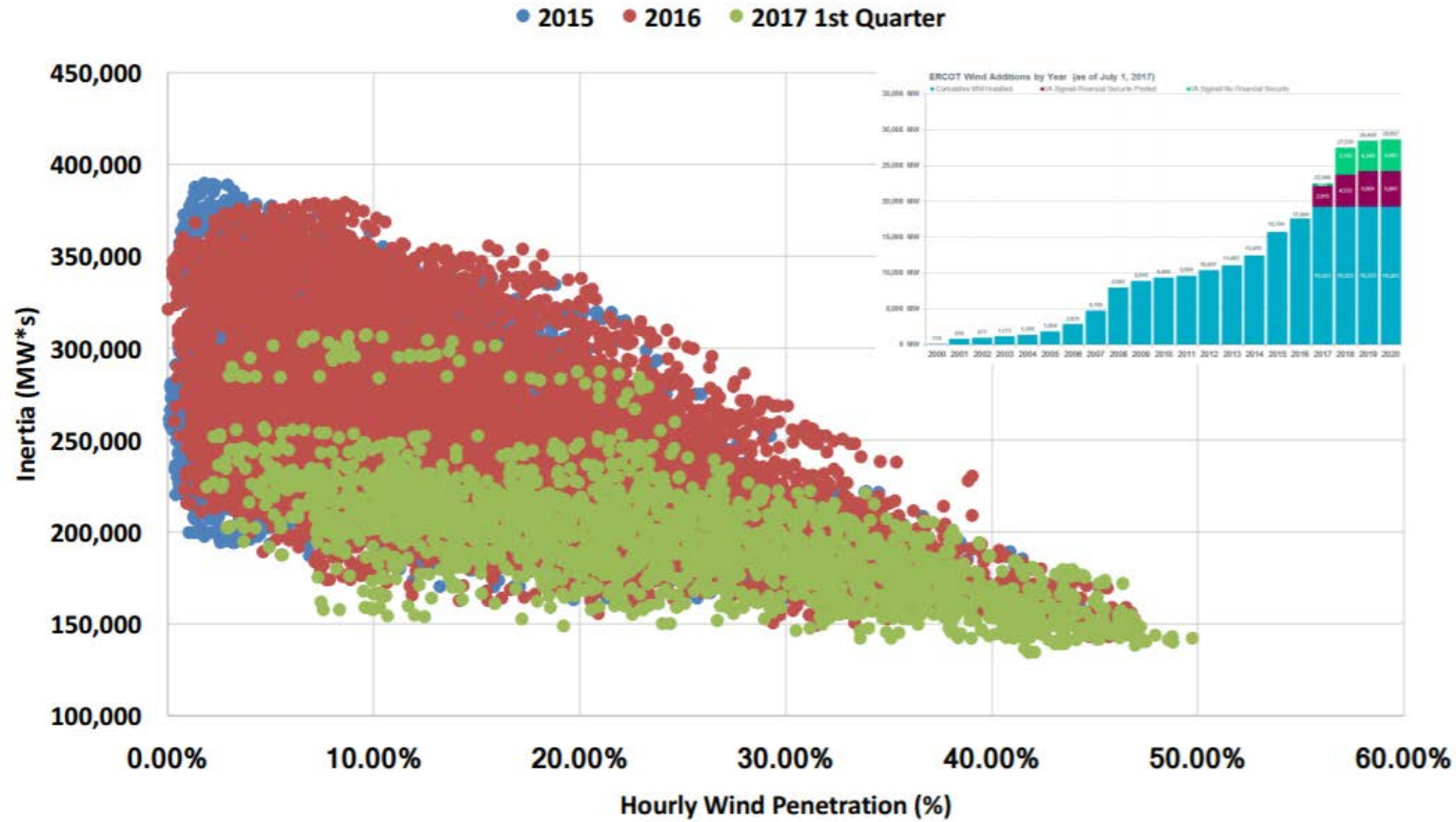
ERCOT Largest N-2

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Inertia Impacts on Frequency

*Data Source: ERCOT Operations Data

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*NERC and **National Labs recognize that large-scale integration of Renewables leads to decline in system inertia, causing a significant reduction of the primary frequency control (PFC) capability.

Gen Loss : 2750 MW   Reserve : 2750 MW
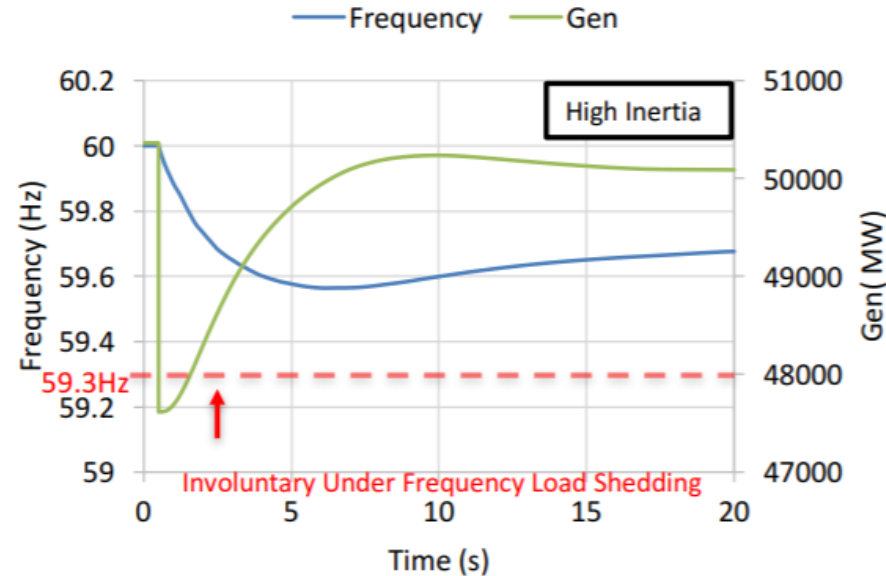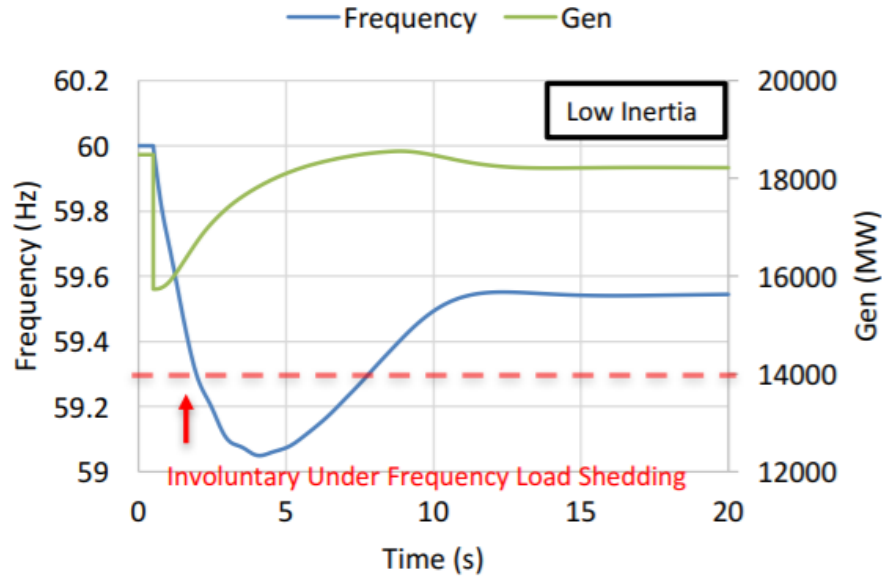
Actual PFR Need ≠ MW Loss ⟷ System Dynamic (impacted by both inertia and PFR) is Crucial

*NERC Frequency Response Initiative, April, 2010
**E. Ela, M. Milligan, B. Kirby, A. Tuohy and D. Brooks, "Alternative approaches for incentivizing the frequency responsive reserve ancillary service," NREL, March 2012

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Comparison: PFR vs FFR

From Generators:
- – **Delivered within 12 to 16 seconds**
- – **From governor response**
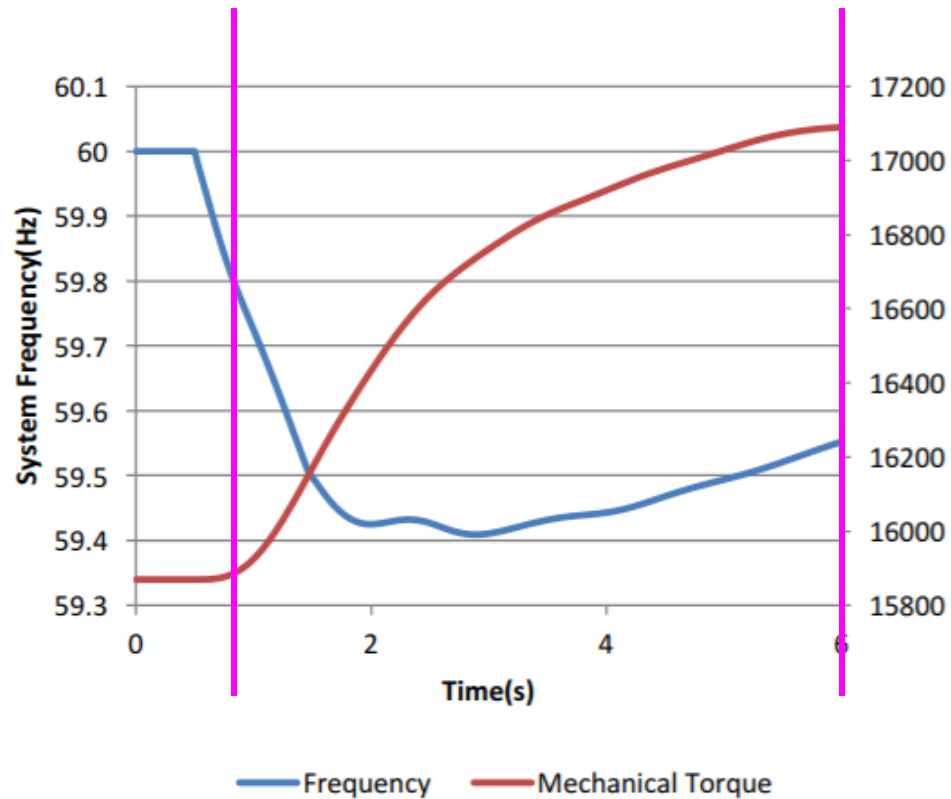
From Load/ other resources:
- – **Delivered within 30 cycles (0.5 seconds)**
- – **Triggered by under frequency relay (59.7Hz)**
- – **Fast Frequency Response (FFR)**

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Loss of 2750 MW Generation

Initial rate of change of frequency (RoCoF) prior to any resource response is solely a function of inertia

Frequency Nadir is determined by primary frequency response and system inertia

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FREEDM SYSTEMS CENTER
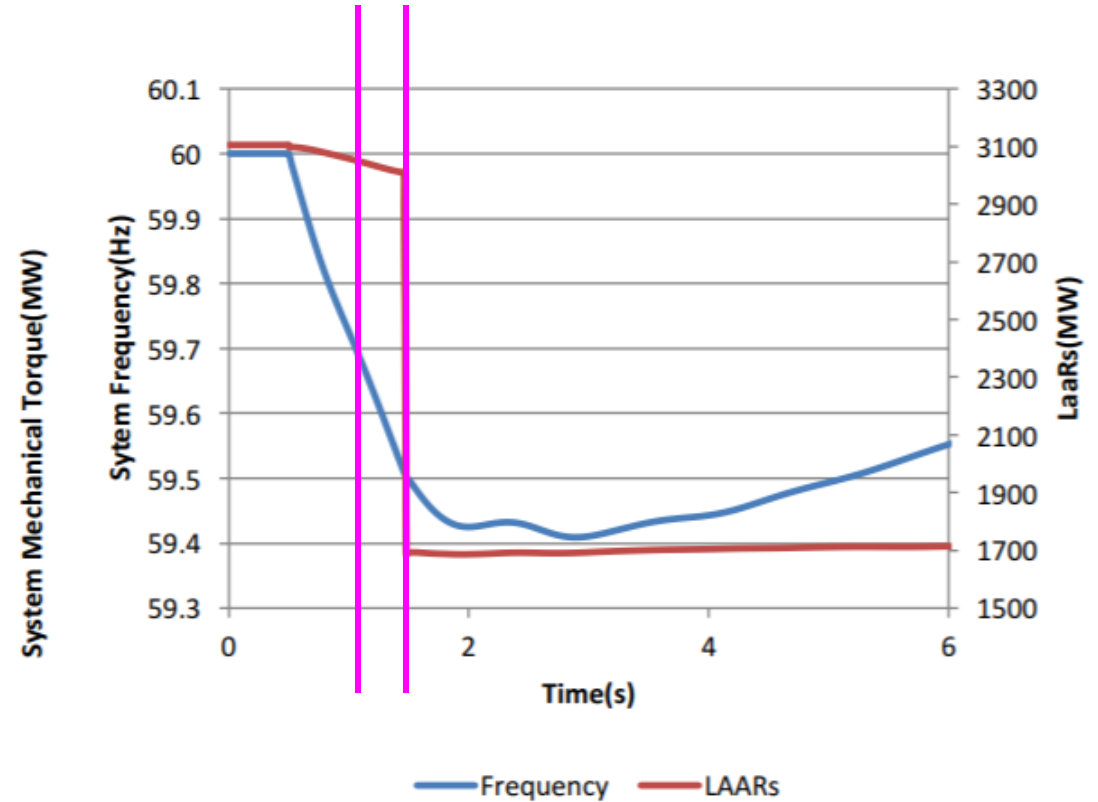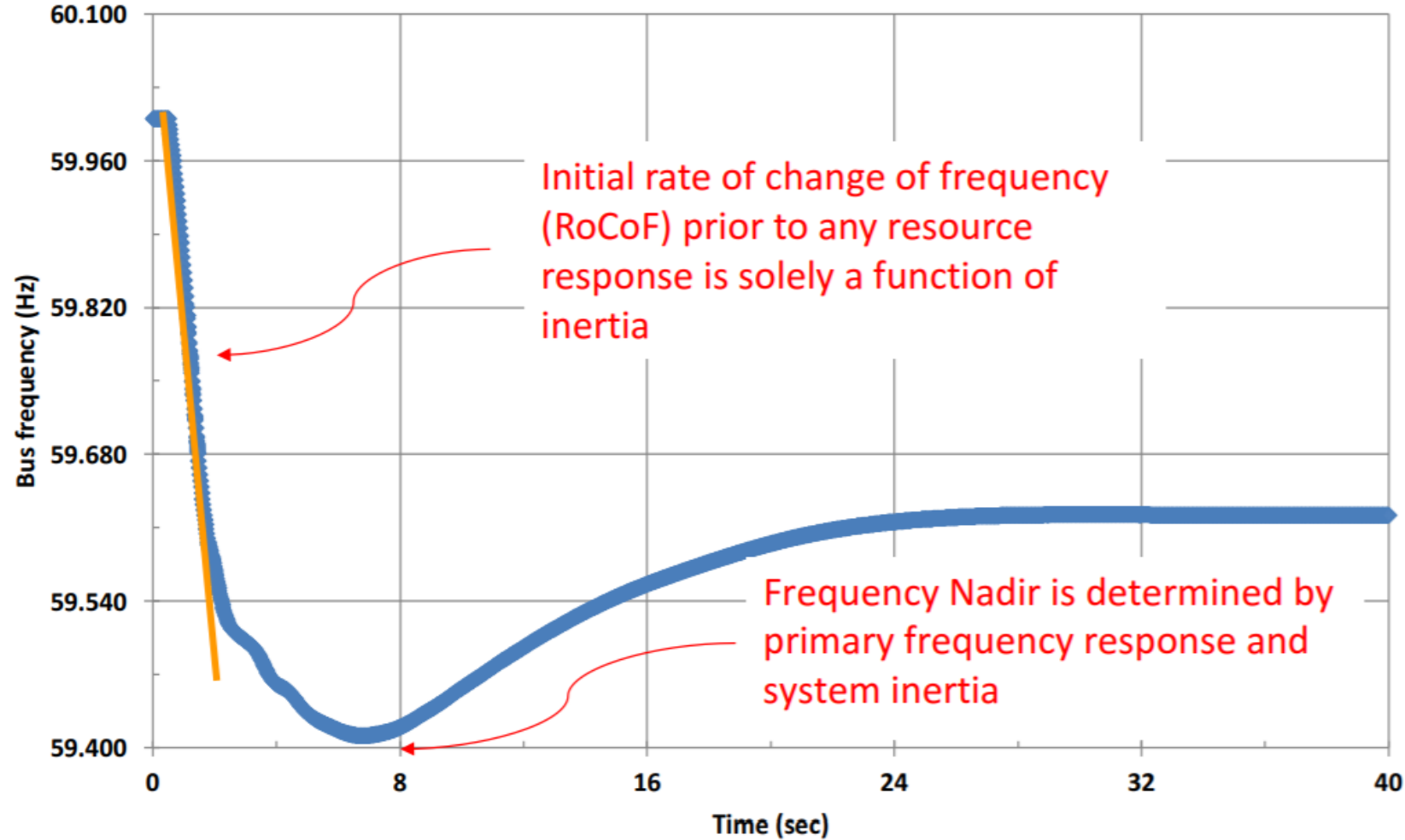
Primary frequency response resources
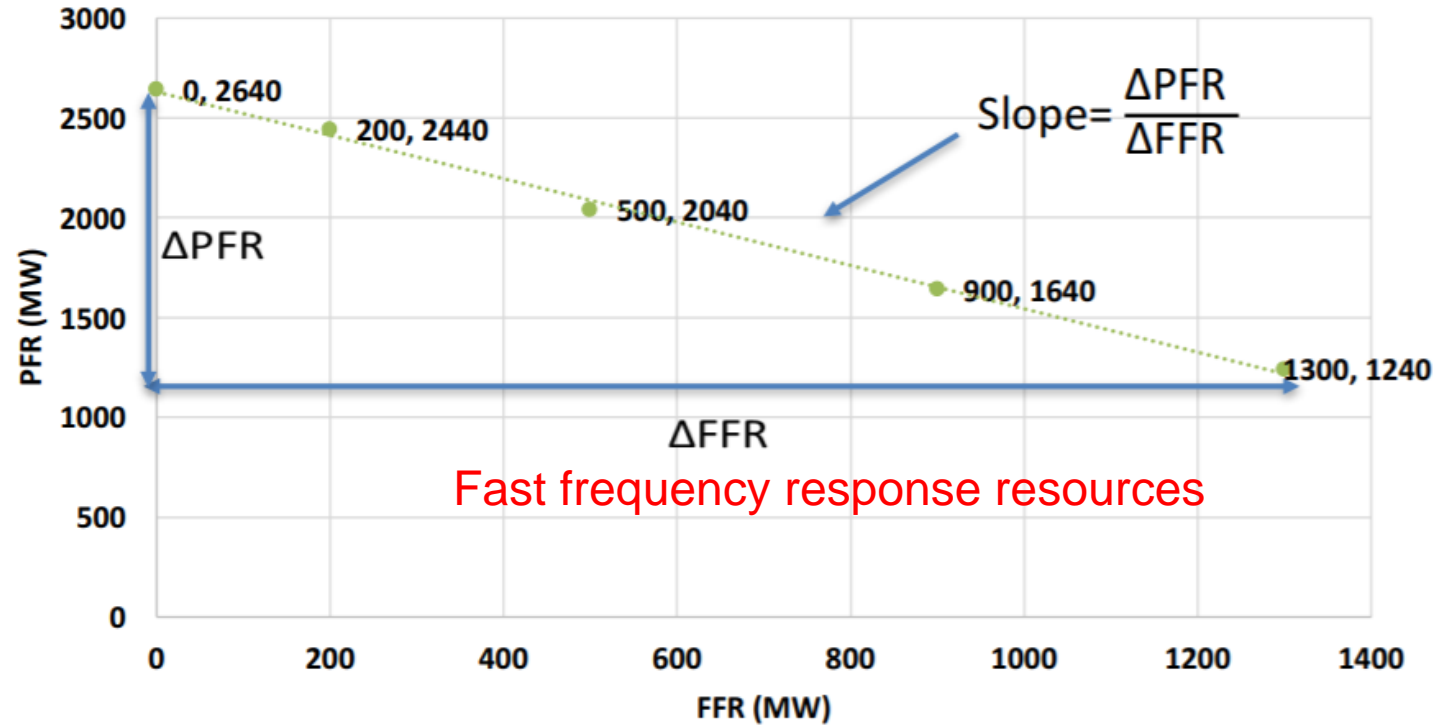
$$\text{PFR/FFR Equivalency Ratio} = -\text{Slope} = -\frac{\Delta PFR}{\Delta FFR}$$

Interpretation: To replace 1MW of FFR, $-\frac{\Delta PFR}{\Delta FFR}$ MW of PFR is needed

$$\left(1MW\ FFR = -\frac{\Delta PFR}{\Delta FFR}\ MW\ PFR\right)$$

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Inertia vs. Net-Load

Fast Frequency Response Resources – provided by DR
Primary Frequency response - Generation

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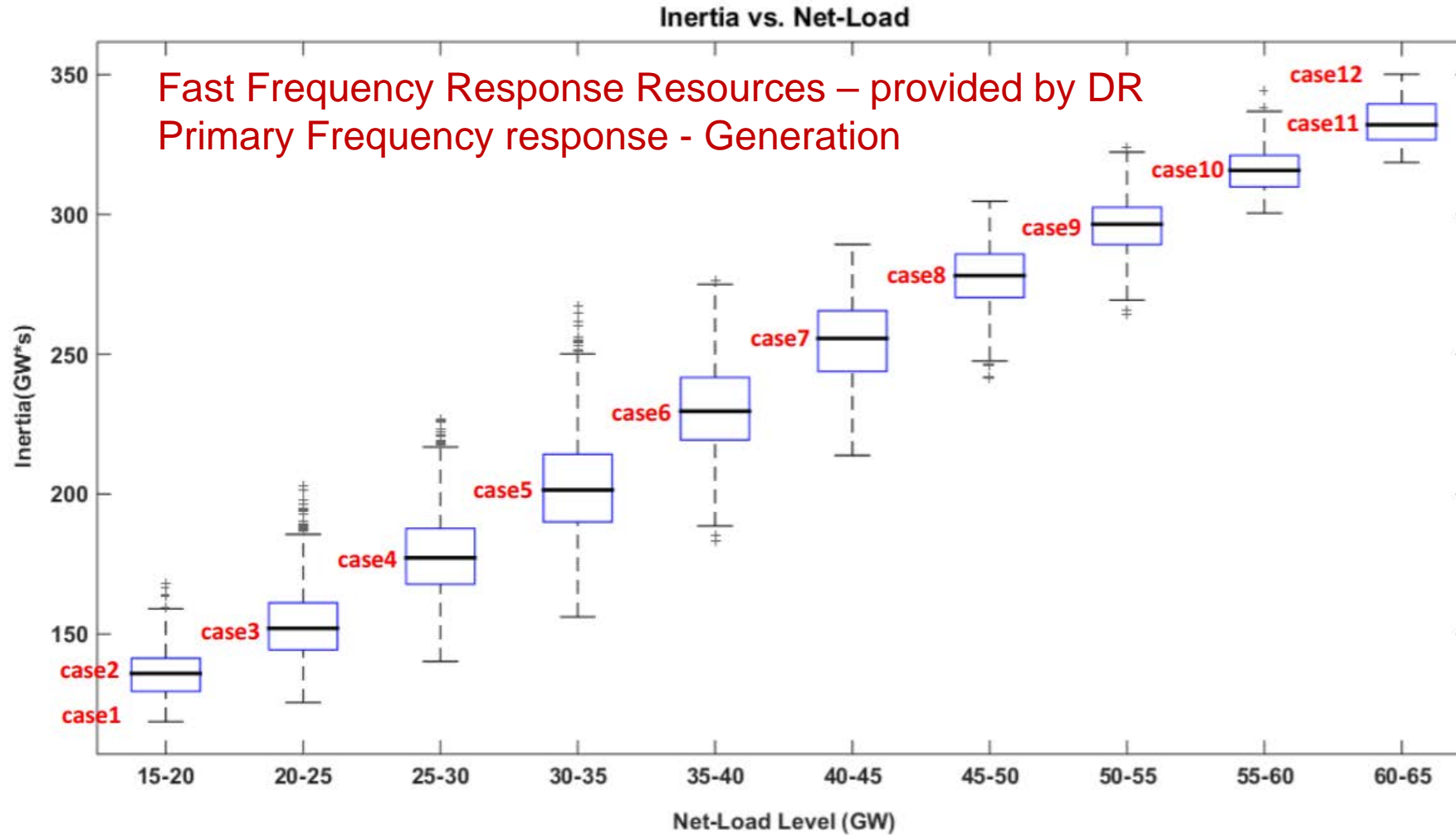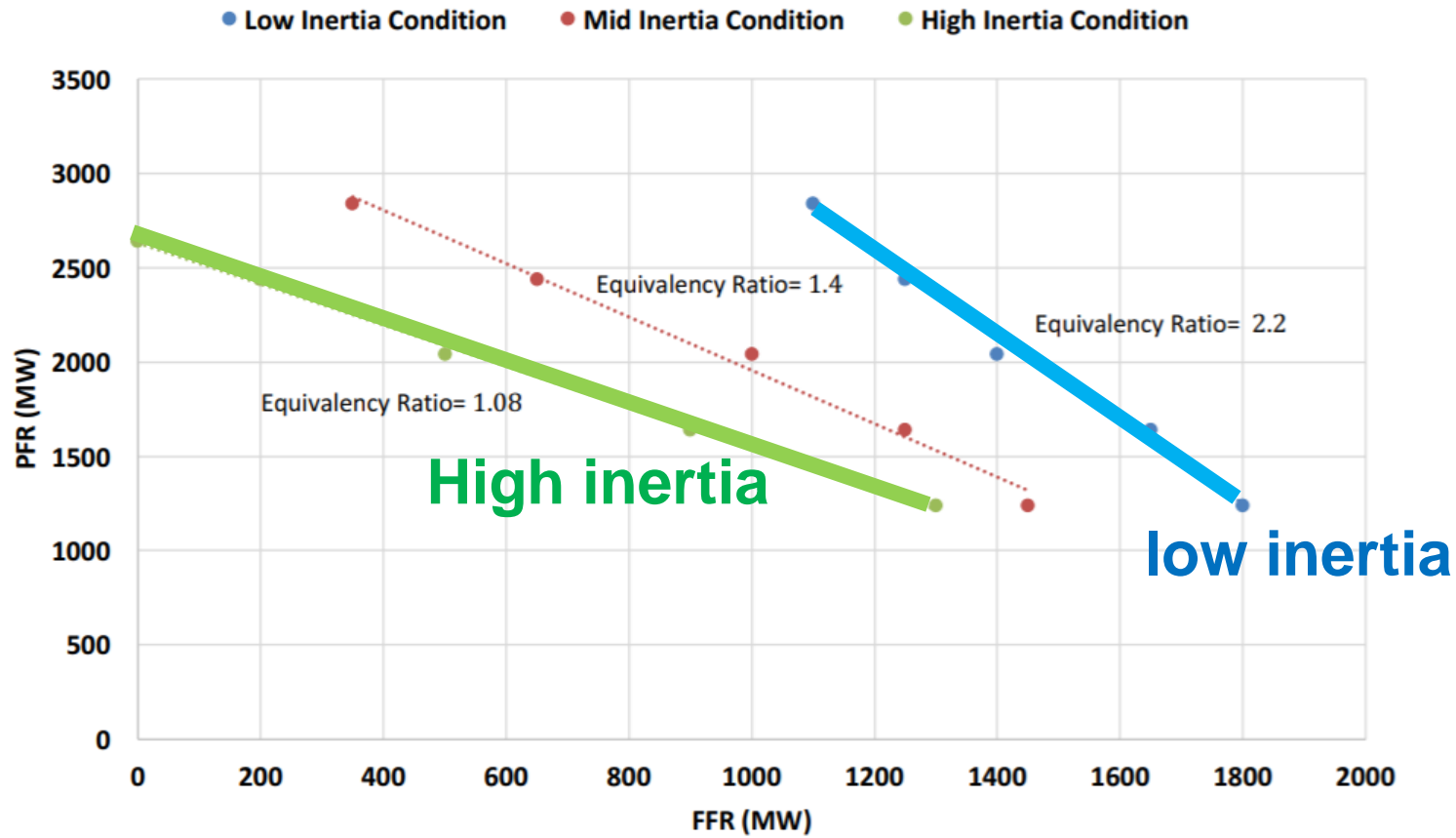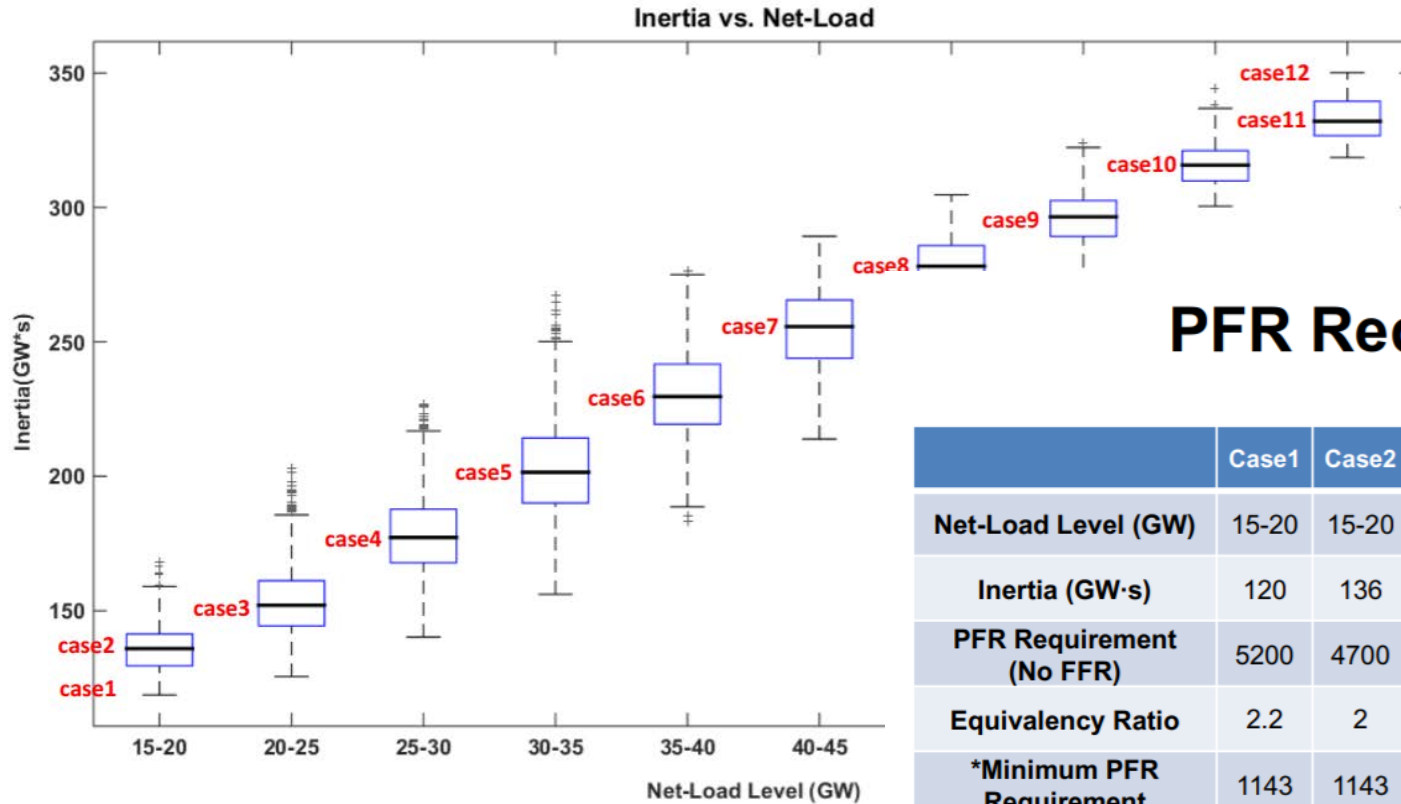
Inertia vs. Net-Load

PFR Requirement Look-up Table

	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10	Case11	Case12
Net-Load Level (GW)	15-20	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	60-65
Inertia (GW·s)	120	136	152	177	202	230	256	278	297	316	332	350
PFR Requirement (No FFR)	5200	4700	3750	3370	3100	3040	2640	2640	2240	2280	2140	2140
Equivalency Ratio	2.2	2	1.5	1.4	1.3	1.25	1.13	1.08	1	1	1	1
*Minimum PFR Requirement	1143	1143	1143	1143	1143	1143	1143	1143	1143	1143	1143	1143
FFR Requirement	1844	1779	1738	1591	1505	1518	1325	1386	1097	1137	997	997

$$FFR\ (Inertia\ i) = \frac{PFR\ Requirement\ (\ Inertia\ i) - PFRmin\_gen}{Equivalency\ Ratio(\ Inertia\ i))}$$

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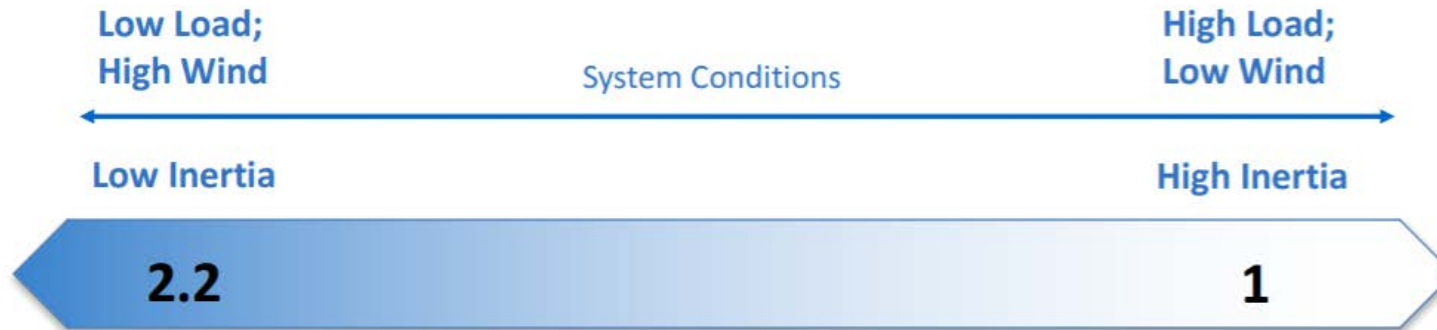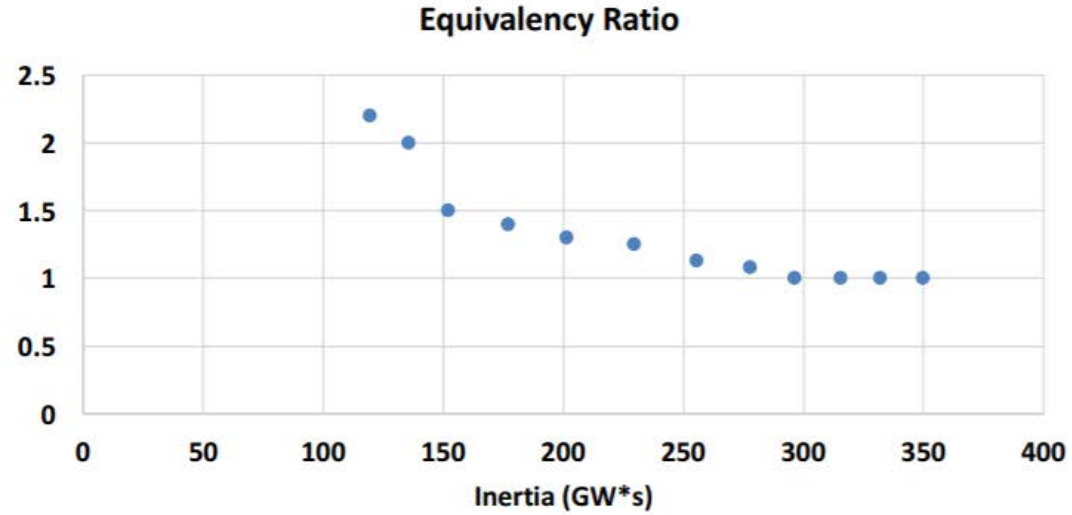
Part 5: Provision of Frequency Response Services

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1. A forward financial electricity market cleared in Day-Ahead
2. Energy and Primary Frequency Response Reserve (PFR) are co-optimized
3. Provide price certainty and discovery for the next operating day

Energy Offers

Demand Bids

PFR/FFR Offers

Inertia Forecast

Day-Ahead Market

Pricing
(Energy, PFR/ FFR)

Awards
(Energy, PFR/ FFR)

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$$\max\left\{\sum_{j=1}^{Nd} b_j(d_j) - \sum_{i=1}^{Ng} f_i(p_i) - \sum_{i=1}^{Ng} f_i^{PFR}\left(p_i^{PFR}\right) - \sum_{j=1}^{Nd} f_j^{FFR}\left(p_j^{PFR}\right)\right\}$$

Energy bid   Energy offer   PFR offer   FFR offer

Maximize The Gap

Bid-based Revenues

Offer-based Costs

Variables:

d_j Energy bid award for load j (MW)

p_i Energy offer award for unit i (MW)

p_i^{PFR} PFR award for unit i (MW)

p_j^{FFR} FFR award for load j (MW)

Parameters:

$b_j(d_j)$ Energy bid for load j ($/MWh)

$f_i(p_i)$ Energy offer for unit i ($/MWh)

$f_i^{PFR}(p_i^{PFR})$ PFR offer for unit i ($/MW)

$f_j^{FFR}(p_j^{FFR})$ FFR offer for load j ($/MW)

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Li, Weifeng, Pengwei Du, and Ning Lu. "Design of a New Primary Frequency Control Market for Hosting Frequency Response Reserve Offers from both Generators and Loads." *IEEE Transactions on Smart Grid* (2017).

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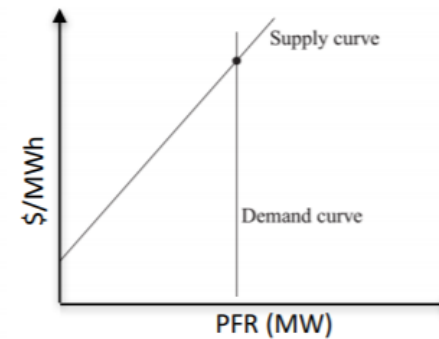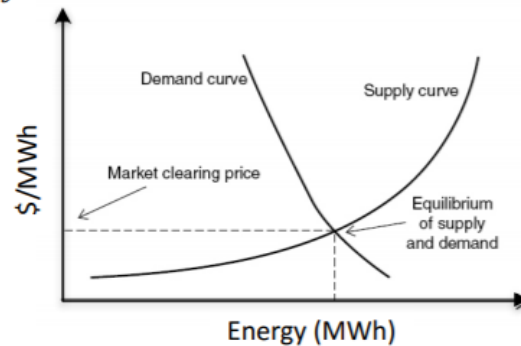
Lagrange Function:

$$L = \sum_{i=1}^{Ng} f_i(p_i) + \sum_{i=1}^{Ng} f_i^{PFR}\left(p_i^{PFR}\right) + \sum_{j=1}^{Nd} f_j^{FFR}\left(p_j^{FFR}\right) - \sum_{j=1}^{Nd} b_j(d_j) + \lambda \times \left(-\sum p_i + \sum d_j\right) - \beta \times \left(\sum_{i=1}^{Ng} p_i^{PFR} + m \times \sum_{j=1}^{Nd} p_j^{FFR} - PFR_{min}\right) - \alpha \times \left(\sum_{i=1}^{Ng} p_i^{PFR} - PFR_{min\_gen}\right) +$$

$$\sum_{i=1}^{Ng} \left(\overline{[\rho_i]}\right)^T \times \left(M \times \begin{bmatrix} P_i \\ p_i^{PFR} \end{bmatrix} - \begin{bmatrix} HSL_i \\ PFR_i \\ HSL_i \end{bmatrix}\right) - \sum_{i=1}^{Ng} \left(\underline{[\rho_i]}\right)^T \times \left(M \times \begin{bmatrix} P_i \\ p_i^{PFR} \end{bmatrix} - \begin{bmatrix} LSL_i \\ PFR_i \\ LSL_i \end{bmatrix}\right) + \sum_{j=1}^{Nd} \left(\overline{\eta_j} \times (p_j^{FFR} - d_j)\right) - \sum_{j=1}^{Nd} \left(\underline{\eta_j} \times p_j^{FFR}\right) + \sum_{j=1}^{Nd} \left(\overline{\theta_j} \times (d_j - D_j)\right) - \sum_{j=1}^{Nd} \left(\underline{\theta_j} \times d_j\right)$$

First-Order Necessary Conditions:

$$\frac{\delta L}{\delta P_i} = \nabla f_i(p_i) - \lambda + M_1^T \times \overline{[\rho_i]} - M_1^T \times \underline{[\rho_i]} = 0$$

$$\frac{\delta L}{\delta p_i^{PFR}} = \nabla f_i^{PFR}(p_i^{PFR}) - \beta - \alpha + M_2^T \times \overline{[\rho_i]} - M_2^T \times \underline{[\rho_i]} = 0$$

$$\frac{\delta L}{\delta p_j^{FFR}} = \nabla f_j^{FFR}(p_j^{FFR}) - m\beta + \overline{\eta_j} - \underline{\eta_j} = 0$$

$$\frac{\delta L}{\delta d_j} = -\nabla b_j(d_j) + \lambda - \overline{\eta_j} + \overline{\theta_j} - \underline{\theta_j} = 0$$

$$\beta \times \left(\sum_{i=1}^{Ng} p_i^{PFR} + m \times \sum_{j=1}^{Nd} p_j^{FFR} - PFR_{min}\right) = 0$$

$$\alpha \times \left(\sum_{i=1}^{Ng} p_i^{PFR} - PFR_{min\_gen}\right) = 0$$

$$\begin{bmatrix} \underline{\rho_{i1}} & & \\ & \underline{\rho_{i2}} & \\ & & \underline{\rho_{i3}} \end{bmatrix} \times \left(M \times \begin{bmatrix} P_i \\ p_i^{PFR} \end{bmatrix} - \begin{bmatrix} LSL_i \\ PFR_i \\ LSL_i \end{bmatrix}\right) = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} \overline{\rho_{i1}} & & \\ & \overline{\rho_{i2}} & \\ & & \overline{\rho_{i3}} \end{bmatrix} \times \left(M \times \begin{bmatrix} P_i \\ p_i^{PFR} \end{bmatrix} - \begin{bmatrix} HSL_i \\ PFR_i \\ HSL_i \end{bmatrix}\right) = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\overline{\eta_j} \times (p_j^{FFR} - d_j) = 0 \qquad \underline{\eta_j} \times p_j^{FFR} = 0$$

$$\underline{\theta_j} \times d_j = 0 \qquad \overline{\theta_j} \times (D_j - d_j) = 0$$

$$\beta, \alpha, \overline{\rho_{ij}}, \underline{\rho_{ij}}, \overline{\eta_i}, \underline{\eta_i}, \overline{\theta_j}, \underline{\theta_j} \geq 0$$

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(PFR Constraints)

$$\sum_{i=1}^{Ng} p_i^{PFR} + m \times \sum_{j=1}^{Nd} p_j^{FFR} \geq PFR_{min}$$

$$\sum_{i=1}^{Ng} p_i^{PFR} \geq PFR_{min\_gen}$$

For each hour:
Inertia can be forecasted based on historical data and thus minimum requirement for PFR and FFR/PFR Equivalency Ratio m are determined as *a priori*

A minimum requirement of PFR from Generator is enforced

Parameters:

m Equivalency ratio between PFR and FFR

PFR_{min} Minimum amount of PFR required (MW)

PFR_{min_gen} Minimum amount of PFR from generators required (MW)

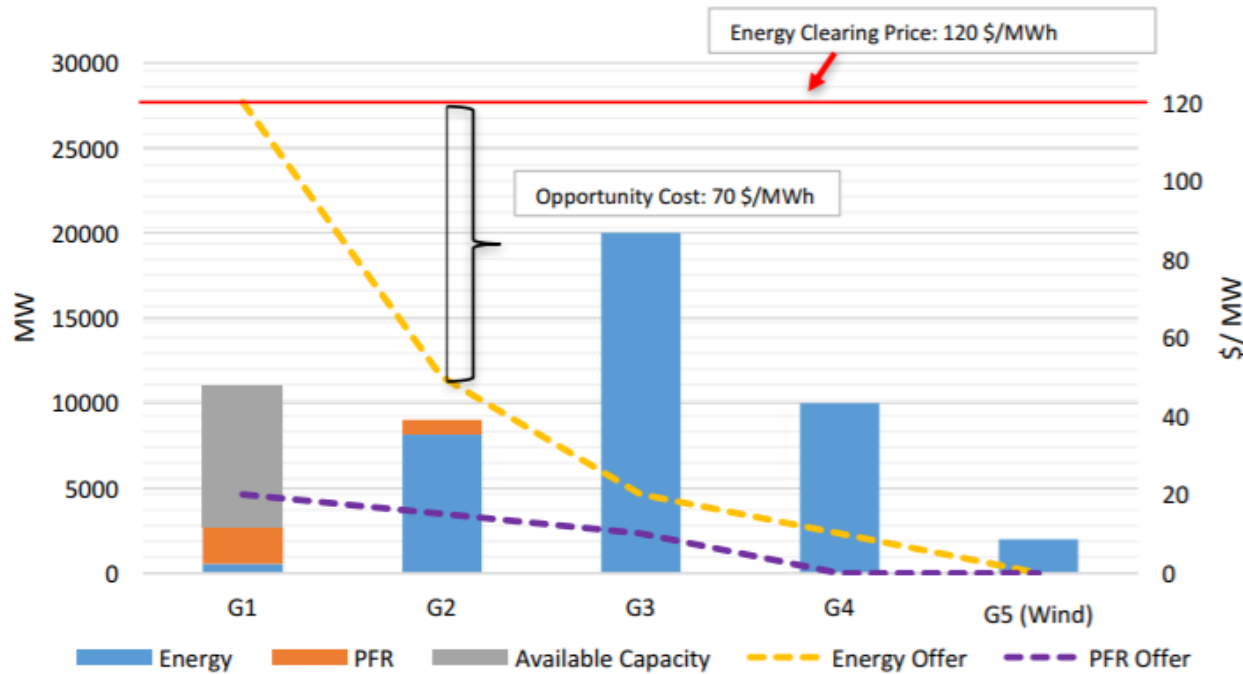|	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10	Case11	Case12
Inertia (GW·s)	120	136	152	177	202	230	256	278	297	316	332	350
PFR Requirement (No FFR)	5200	4700	3750	3370	3100	3040	2640	2640	2240	2280	2140	2140
FFR/PFR Ratio	2.2	2	1.5	1.4	1.3	1.25	1.13	1.08	1	1	1	1
Minimum PFR Requirement from Gen	1143	1143	1143	1143	1143	1143	1143	1143	1143	1143	1143	1143
FFR Requirement	1844	1779	1738	1591	1505	1518	1325	1386	1097	1137	997	997

Eliminate price spikes

Assumed System Condition :
Inertia :230 GW*s, PFR min_gen=1143 MW, PFR min=3040 MW, PFR/FFR Ratio=1.25

Generator	Capacity (MW)	Energy Offers ($/MWh)	PFR Capacity (MW)	PFR offers ($/MW)
G1	[0,11000]	120	[0,2200]	20
G2	[0,9000]	50	[0,1800]	15
G3	[0,20000]	20	[0,4000]	10
G4	[0,10000]	10	-	-
G5 (Wind)	[0,2000]	0.01	-	-

Load	Total Load (MW)	Energy Bids ($/MWh)	FFR Capacity (MW)	FFR offers ($/MW)
L1(must serve)	26200	9000	-	-
L2(must serve)	8000	8000	-	-
L3(must serve)	6000	8000	-	-
L4	400	30	[0,400]	-
L5	200	25	-	-

NO FFR

Energy/PFR (G1)	40/**2200**
Energy/PFR (G2)	8160/**840**
Energy/PFR (G3)	20000/0
Energy/PFR (G4)	10000/-
Energy/PFR (G5)	2000/-
Energy/FFR (L1)	26200/-
Energy/FFR (L2)	8000/-
Energy/FFR (L3)	6000/-
Energy/FFR (L4)	0/0
Energy/FFR (L5)	0/0

Energy Clearing Price	$\lambda=120$ ($/MWh)
PFR Clearing Price	$\alpha+\beta=85$ ($/MW)
FFR Clearing Price	$m\beta=106.25$ ($/MW)
λ, α, β	120,0,85

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Assumed System Condition :
Inertia :230 GW*s, PFR min_gen=1143 MW, PFR min=3040 MW, PFR/FFR Ratio=1.25

Generator	Capacity (MW)	Energy Offers ($/MWh)	PFR Capacity (MW)	PFR offers ($/MW)
G1	[0,11000]	120	[0,2200]	20
G2	[0,9000]	50	[0,1800]	15
G3	[0,20000]	20	[0,4000]	10
G4	[0,10000]	10	-	-
G5 (Wind)	[0,2000]	0.01	-	-

Load	Total Load (MW)	Energy Bids ($/MWh)	FFR Capacity (MW)	FFR offers ($/MW)
L1(must serve)	26200	9000	-	-
L2(must serve)	8000	8000	-	-
L3(must serve)	6000	8000	-	**NO FFR**
L4	400	30	[0,400]	-
L5	200	25	-	-

PFR Clearing Price: 85$/MW

70 $/MW

Legend: Energy | PFR | Available Capacity | Energy Offer | PFR Offer

Energy/PFR (G1)	40/**2200**
Energy/PFR (G2)	8160/**840**
Energy/PFR (G3)	20000/0
Energy/PFR (G4)	10000/-
Energy/PFR (G5)	2000/-
Energy/FFR (L1)	26200/-
Energy/FFR (L2)	8000/-
Energy/FFR (L3)	6000/-
Energy/FFR (L4)	0/0
Energy/FFR (L5)	0/0

Energy Clearing Price	$\lambda=120$ ($/MWh)
PFR Clearing Price	$\alpha+\beta=85$ ($/MW)
FFR Clearing Price	$m\beta=106.25$ ($/MW)
λ, α, β	120,0,85

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Generator	Capacity (MW)	Energy Offers ($/MWh)	PFR Capacity (MW)	PFR offers ($/MW)
G1	[0,11000]	120	[0,2200]	20
G2	[0,9000]	50	[0,1800]	15
G3	[0,20000]	20	[0,4000]	10
G4	[0,10000]	10	-	-
G5 (Wind)	[0,2000]	0.01	-	-

Load	Total Load (MW)	Energy Bids ($/MWh)	FFR Capacity (MW)	FFR offers ($/MW)
L1(must serve)	26200	9000	-	-
L2(must serve)	8000	8000	-	-
L3(must serve)	6000	8000	-	-
L4	400	30	[0,400]	8
L5	200	25	-	-

With FFR

Energy/PFR (G1)	0/**2200**
Energy/PFR (G2)	8360/**640**
Energy/PFR (G3)	20000/0
Energy/PFR (G4)	10000/-
Energy/PFR (G5)	2000/-
Energy/FFR (L1)	26200/-
Energy/FFR (L2)	8000/-
Energy/FFR (L3)	6000/-
Energy/FFR (L4)	160/**160**
Energy/FFR (L5)	0/0

Energy Clearing Price	$\lambda=87$	($/MWh)
PFR Clearing Price	$\alpha+\beta=52$	($/MW)
FFR Clearing Price	$m\beta=65$	($/MW)
λ, α, β	87,0,52	

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Generator	Capacity (MW)	Energy Offers ($/MWh)	PFR Capacity (MW)	PFR offers ($/MW)
G1	[0,11000]	120	[0,2200]	20
G2	[0,9000]	50	[0,1800]	15
G3	[0,20000]	20	[0,4000]	10
G4	[0,10000]	10	-	-
G5 (Wind)	[0,2000]	0.01	-	-

Load	Total Load (MW)	Energy Bids ($/MWh)	FFR Capacity (MW)	FFR offers ($/MW)
L1(must serve)	26200	9000	-	-
L2(must serve)	8000	8000	-	-
L3(must serve)	6000	8000	-	-
L4	400	30	[0,400]	8
L5	200	25	-	-

With FFR

Energy/PFR (G1)	0/**2200**
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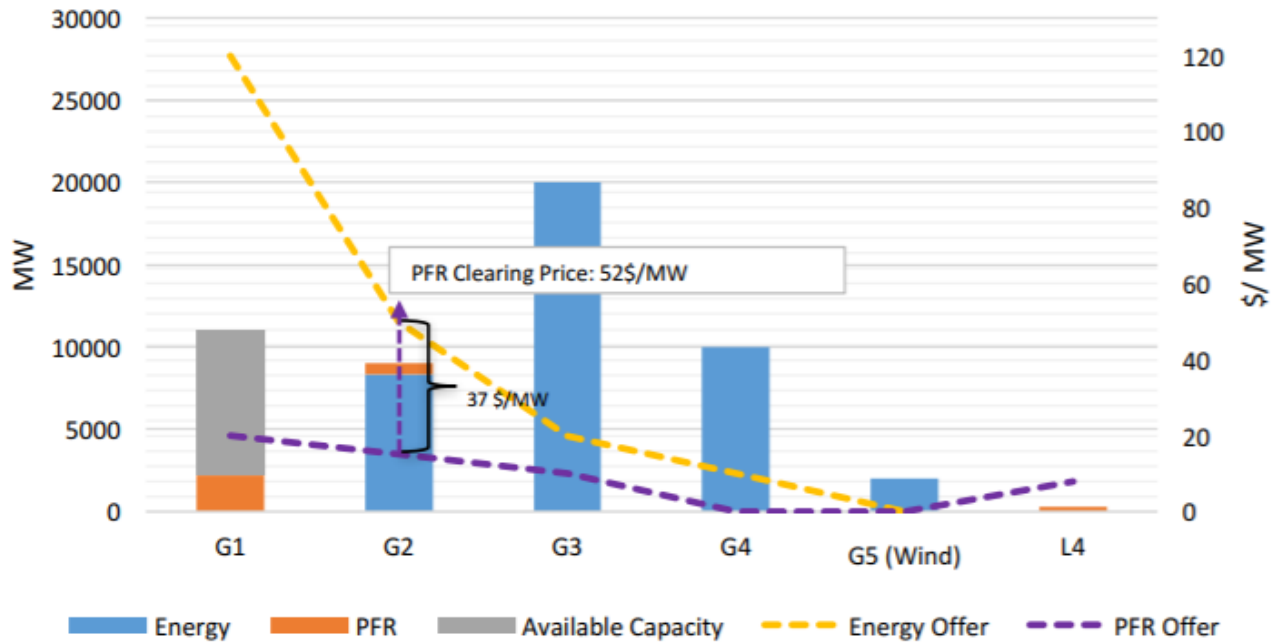|		
Energy Clearing Price	$\lambda=87$	($/MWh)
PFR Clearing Price	$\alpha+\beta=52$	($/MW)
FFR Clearing Price	$m\beta=65$	($/MW)
λ, α, β	87,0,52	

PFR Clearing Price: 52$/MW

37 $/MW

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Legend: Energy | PFR | Available Capacity | Energy Offer | PFR Offer

Assumed System Condition :
Inertia :230 GW*s, PFR min_gen=1143 MW, PFR min=3040MW, PFR/FFR Ratio=1.25

Generator	Capacity (MW)	Energy Offers ($/MWh)	PFR Capacity (MW)	PFR offers ($/MW)
G1	[0,11000]	120	[0,2200]	20
G2	[0,9000]	50	[0,1800]	15
G3	[0,20000]	20	[0,4000]	10
G4	[0,10000]	10	-	-
G5 (Wind)	[0,2000]	0.01	-	-

Load	Total Load (MW)	Energy Bids ($/MWh)	FFR Capacity (MW)	FFR offers ($/MW)
L1(must serve)	26200	9000	-	-
L2(must serve)	8000	8000	-	-
L3(must serve)	6000	8000	-	-
L4	400	30	[0,400]	1-30
L5	200	25	-	-

Allow the FFR resources to provide frequency service will increase the price elasticity.
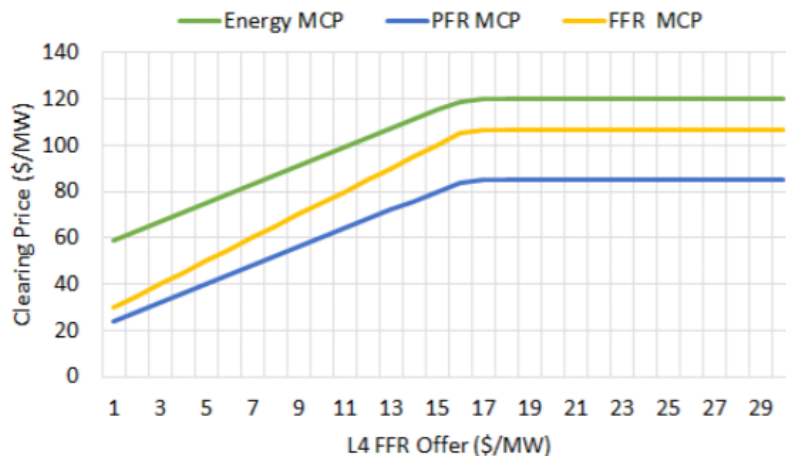
- When L4 increases its bid from $1/MW to $17/MW, the resulting price mitigation effect is diminishing.

- The cost for L4 to provide FFR increases to a certain point, the revenue it receives for providing FFR can no longer offset the additional payment made to purchase energy.

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