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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

Outline

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

GridWrX Lab: Faculties

Research Areas

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

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GridWrX Lab: PHD Students

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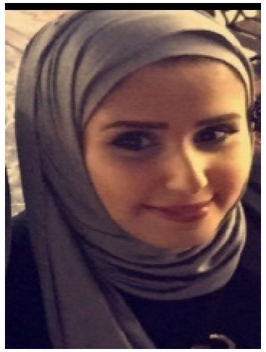
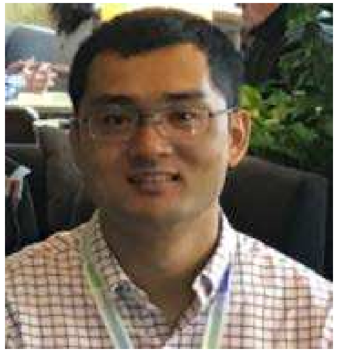
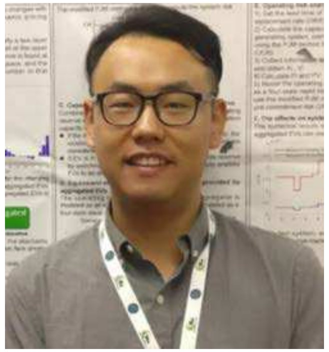
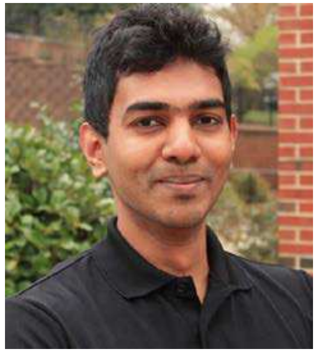
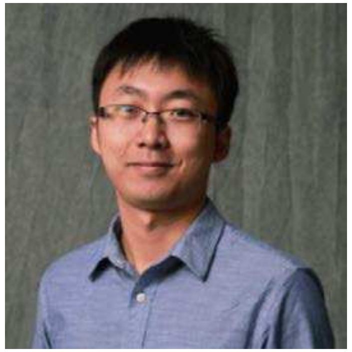


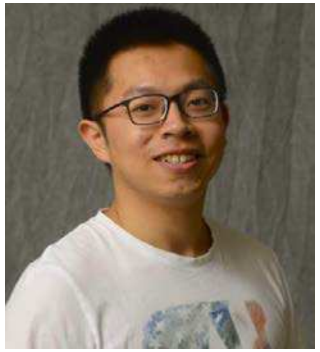
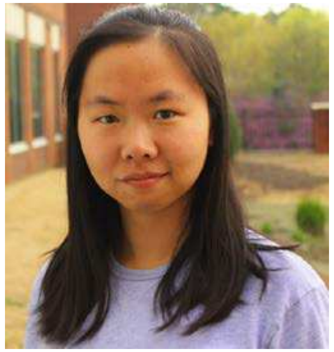




- GridWrx lab is currently the home of **15** PhD students
- We also host undergraduate researchers, master students, and visiting scholars to maintain a diversified group.


GridWrX Lab: Dr. Lu's Research Group

Microgrid, Home and Building Energy Management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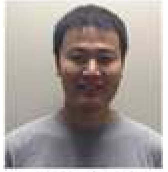
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Smart House
EMS Software and Hardware Implementation

Load Emulator
EMS Software and Hardware Implementation

Load Forecaster
Forecasting Algorithm
Data-driven Models

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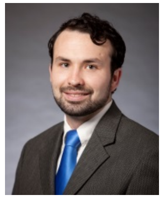
Energy Storage, Renewable Integration, and Smart Planning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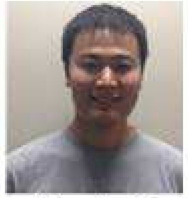
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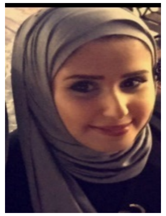
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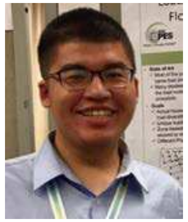
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Part 1: Background

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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.

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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.
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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.
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Energy Storage Options

- 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

Classification of ES Technologies

Direct Storage

Electrical charges:
Capacitors
SEMS

Indirect Storage

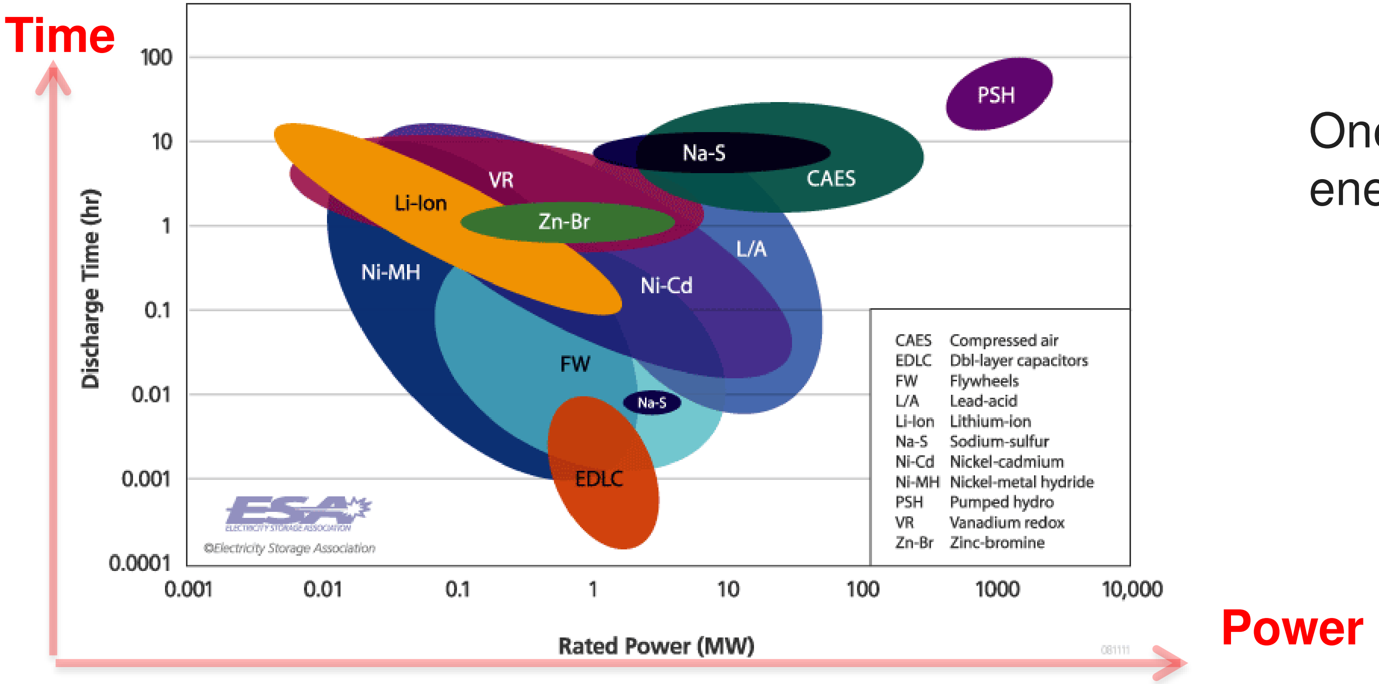
(via 1-way or 2-way energy conversion)

Potential
Pumped hydro
compress air

Kinetic
Flywheel

Chemical
Batteries

Thermal
Water heaters,
air conditioners



One-directional
energy conversion

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

Applications

- 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

Applications

- Traditional (Energy Markets)
  - Backup
  - Peak shaving
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- Advanced (Ancillary Services)
  - Regulation
  - **Load following service**
  - **Frequency response**
  - Spinning/non-spinning reserves
  - Reactive power support

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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.
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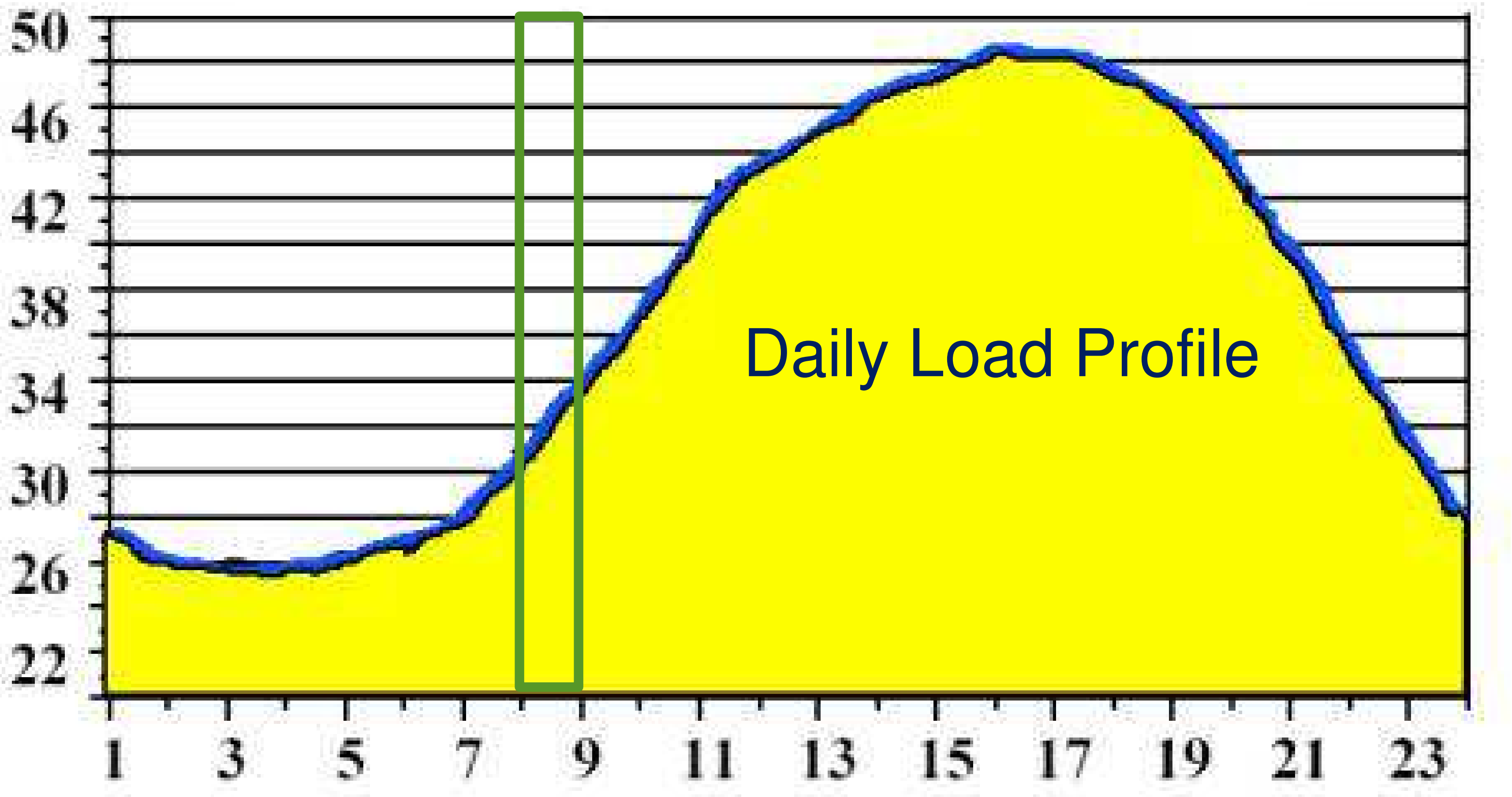
An Example of Load Balancing

Intra-hour Applications



An Example of Load Balancing

Balance the mismatches between the load forecast and the actual load

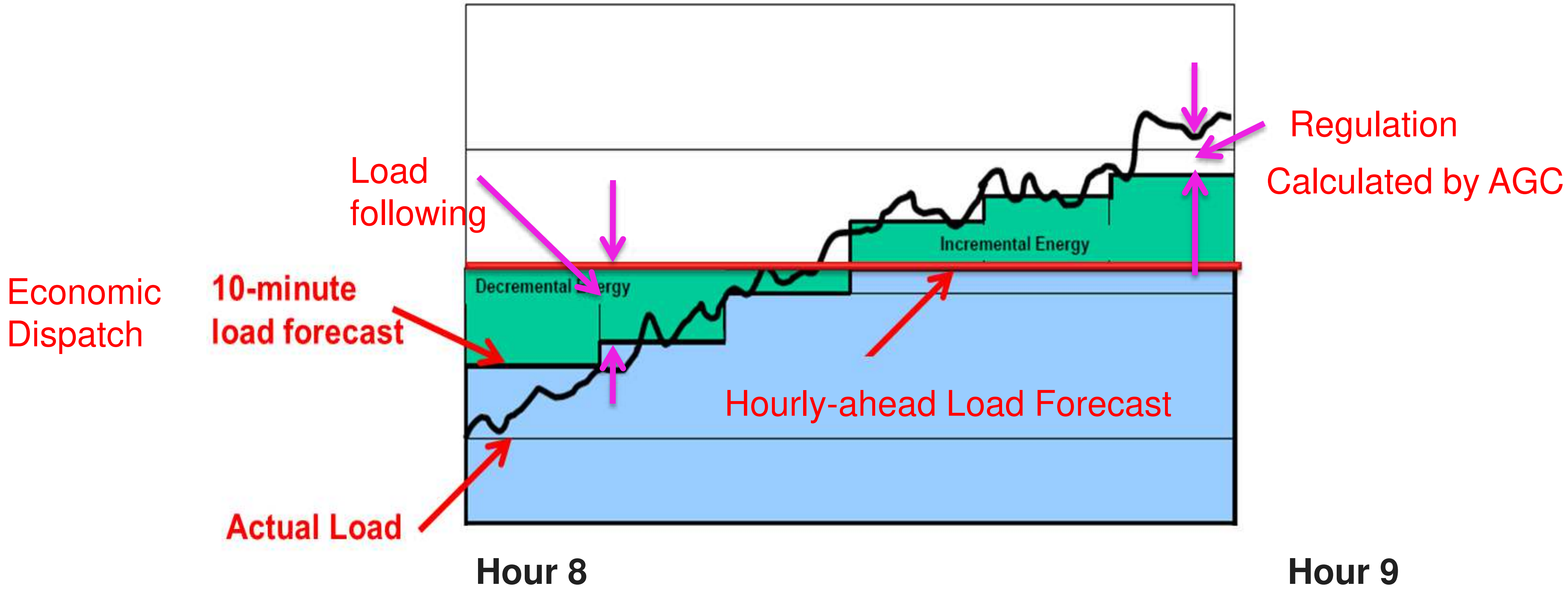
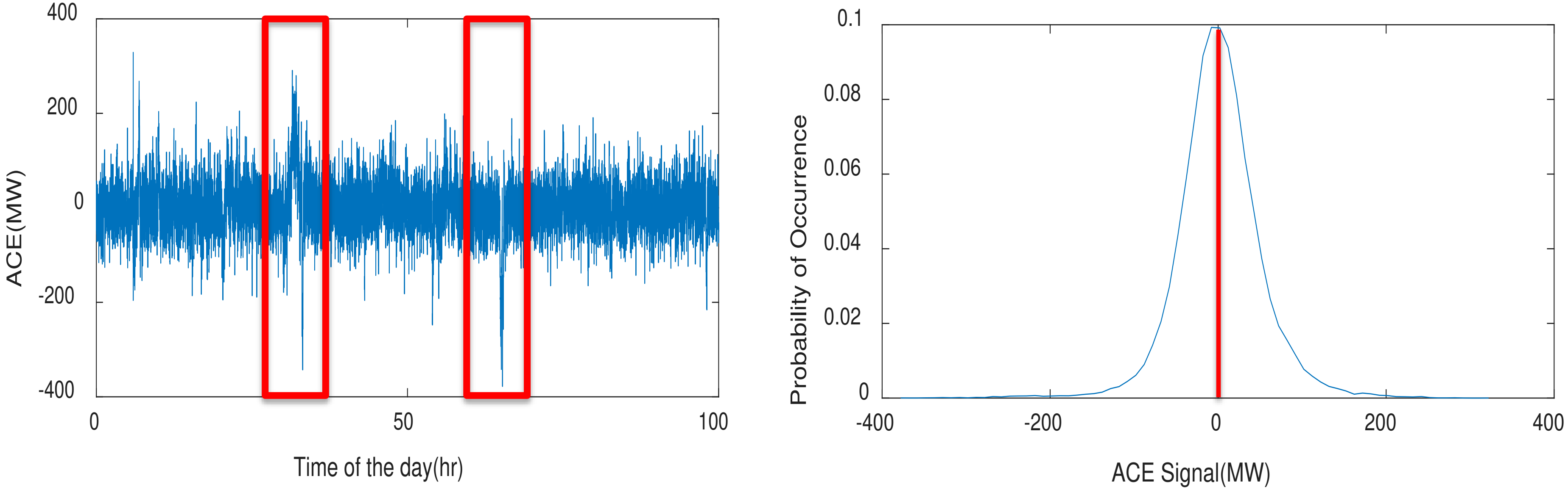


Figure by Craig Taylor and Don DeBerry, presented at 2002 OSIsoft T&D Users Conference

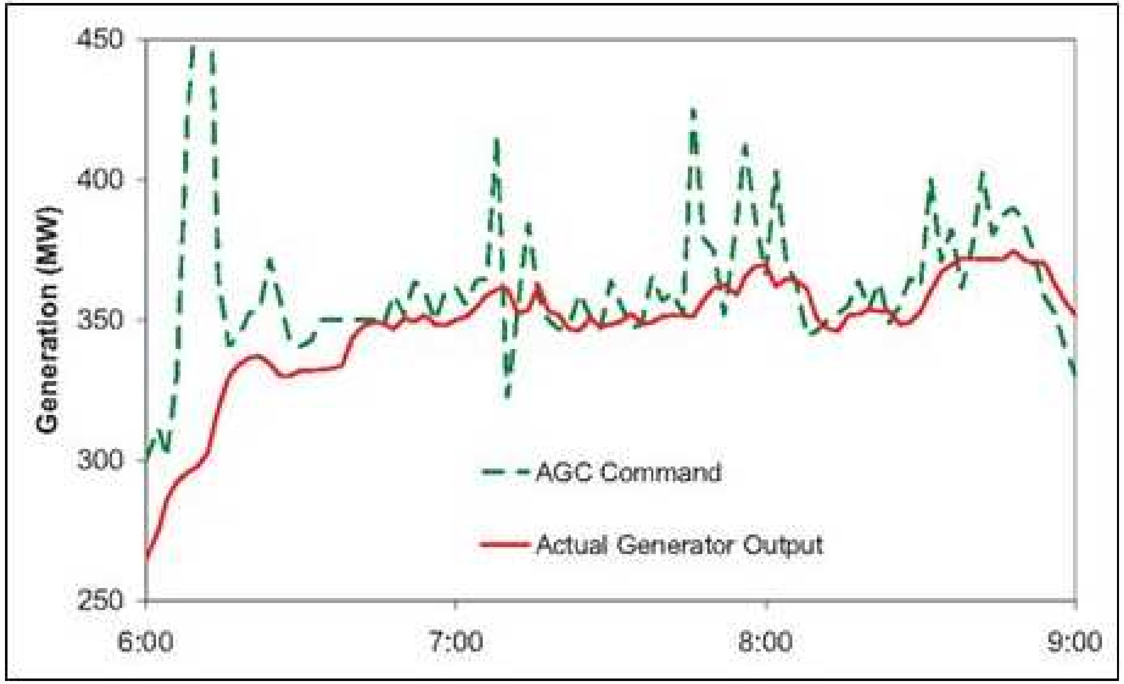
Regulation Service

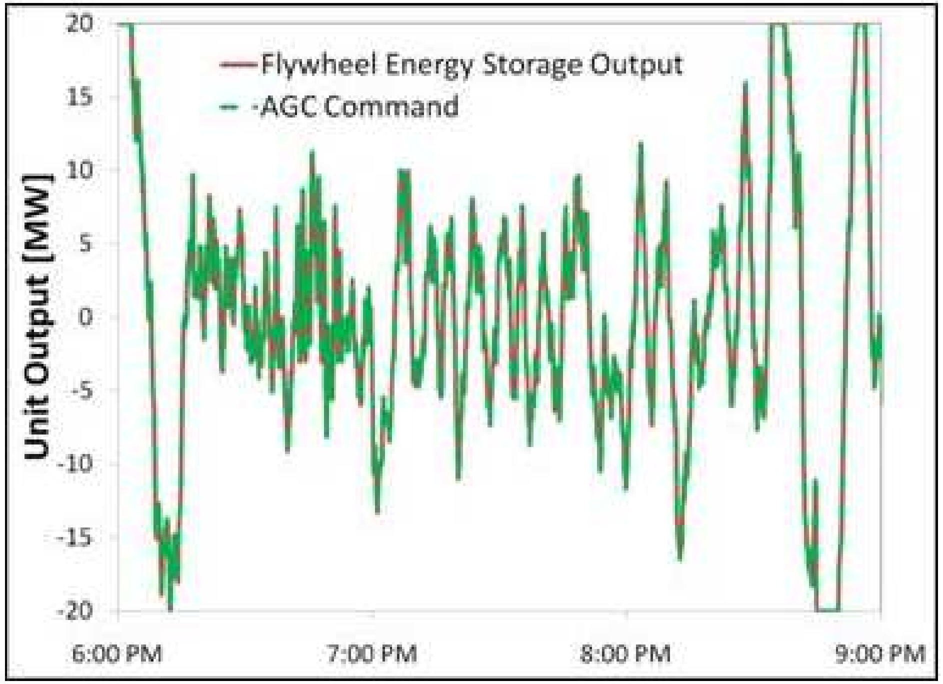
- **Regulation services:** balances generation and load in real-time to maintain system frequency and tie-line power flows at the scheduled values.
- **Inputs:** Area Control Error(ACE) and Tie-line Flow Deviations.
- **Signal resolution:** 2-10 seconds
- **Characteristics:** mostly energy neutral, random in magnitude (very hard to forecast)

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



Energy Storage for Regulation Service





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

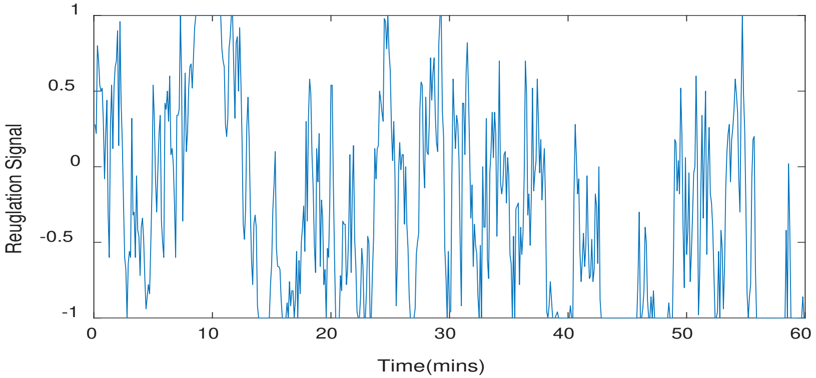
Technical Challenges

- 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**.

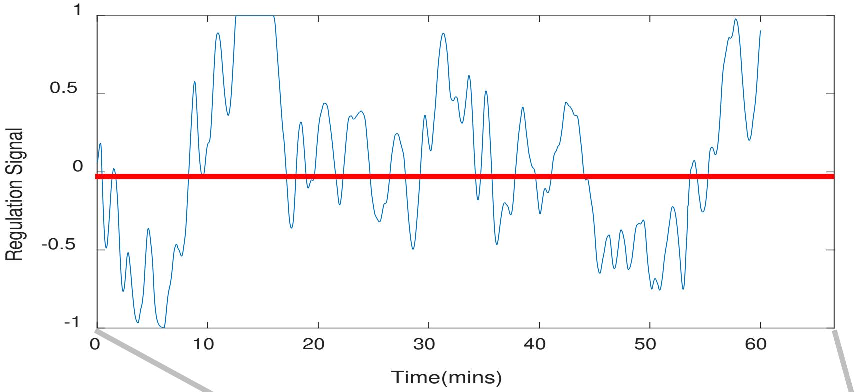
Enabling Factors

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

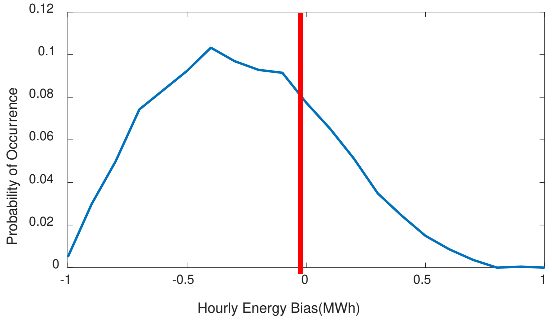
Design Considerations: **FERC Order 784** requires the **improvement of signal design** considering the state of charge constraint of energy storage system



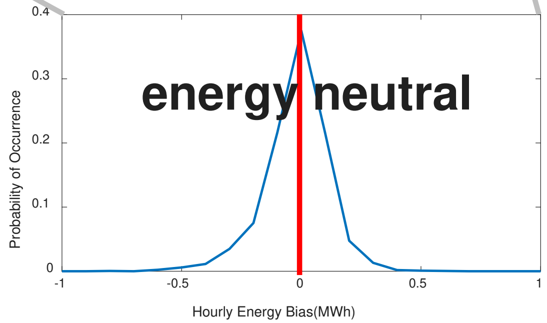
One hour NY-ISO regulation signal



One hour PJM RegD signal



PDF of PJM RegA



PDF of PJM RegD

Pay-for-performance Market Mechanism

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 $\boldsymbol{M}$: 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 $\boldsymbol{\lambda}$: A value between 0 and 1, represent the response accuracy with respect to the regulation instructions. A general penalization format is as follows:

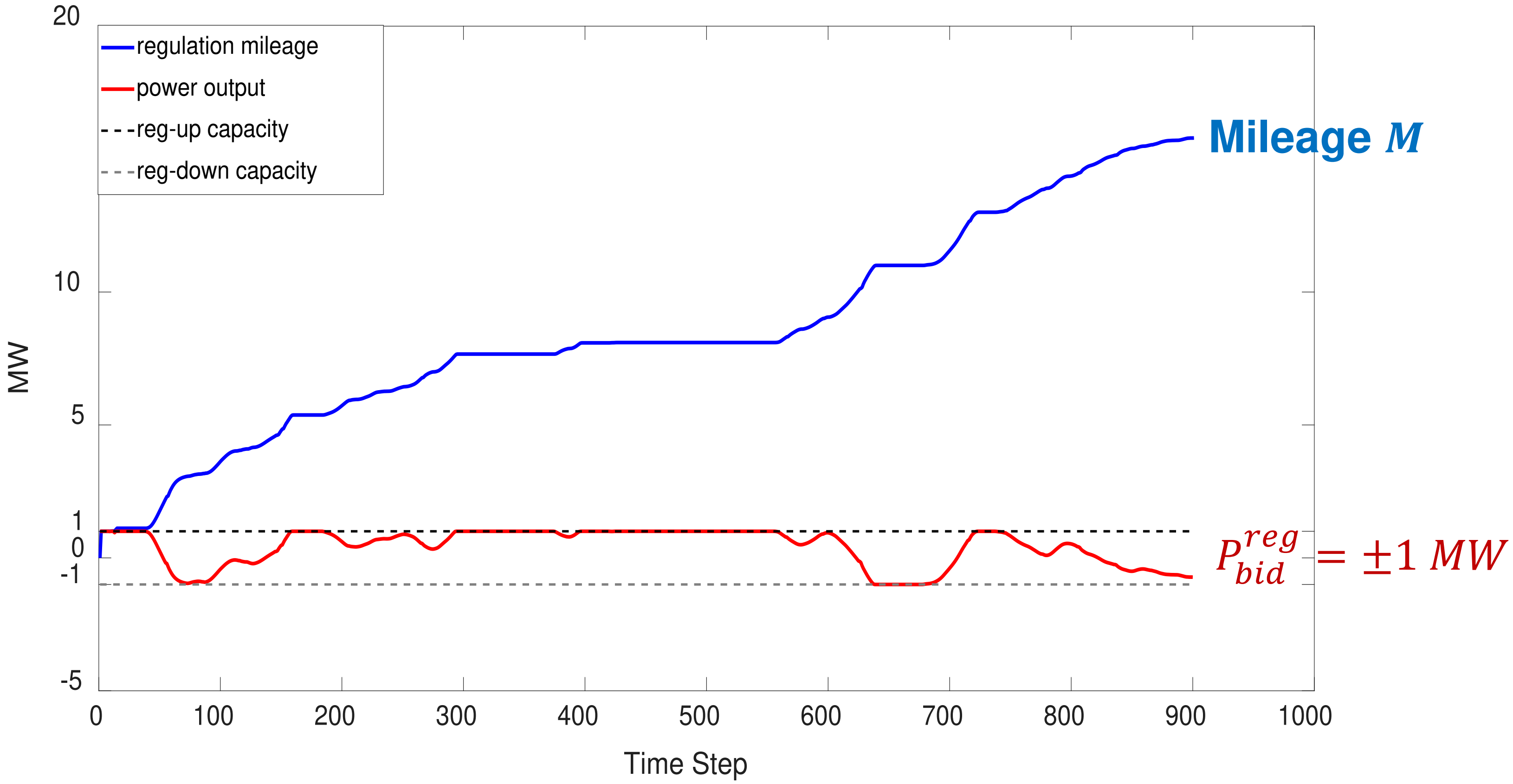
$$\text{Payment} = P_{bid}^{reg}(\rho_c + \boldsymbol{\lambda}\text{M}\rho_M)$$

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

Regulation Mileage

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

$$M = \sum_{0}^{T} \frac{\left|P_t^{reg} - P_{t-1}^{reg}\right|}{P_{bid}^{reg}}$$



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Part 3: Modeling of Energy Storage Devices

NSF

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

Cost-benefit Study Models

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

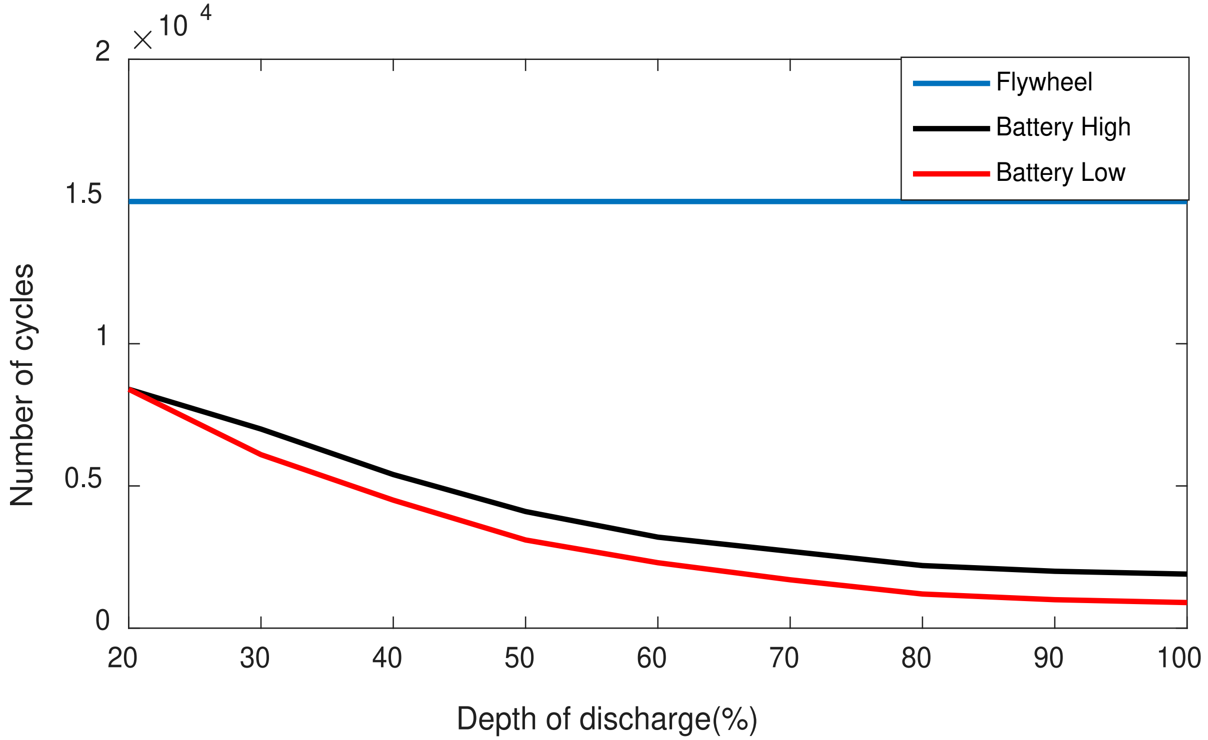
Cost-of-service $$C = C_{install} + C_{O\&M}$$

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

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

Battery Lifetime Estimation Methods

- 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



Two Types of Services Mechanism

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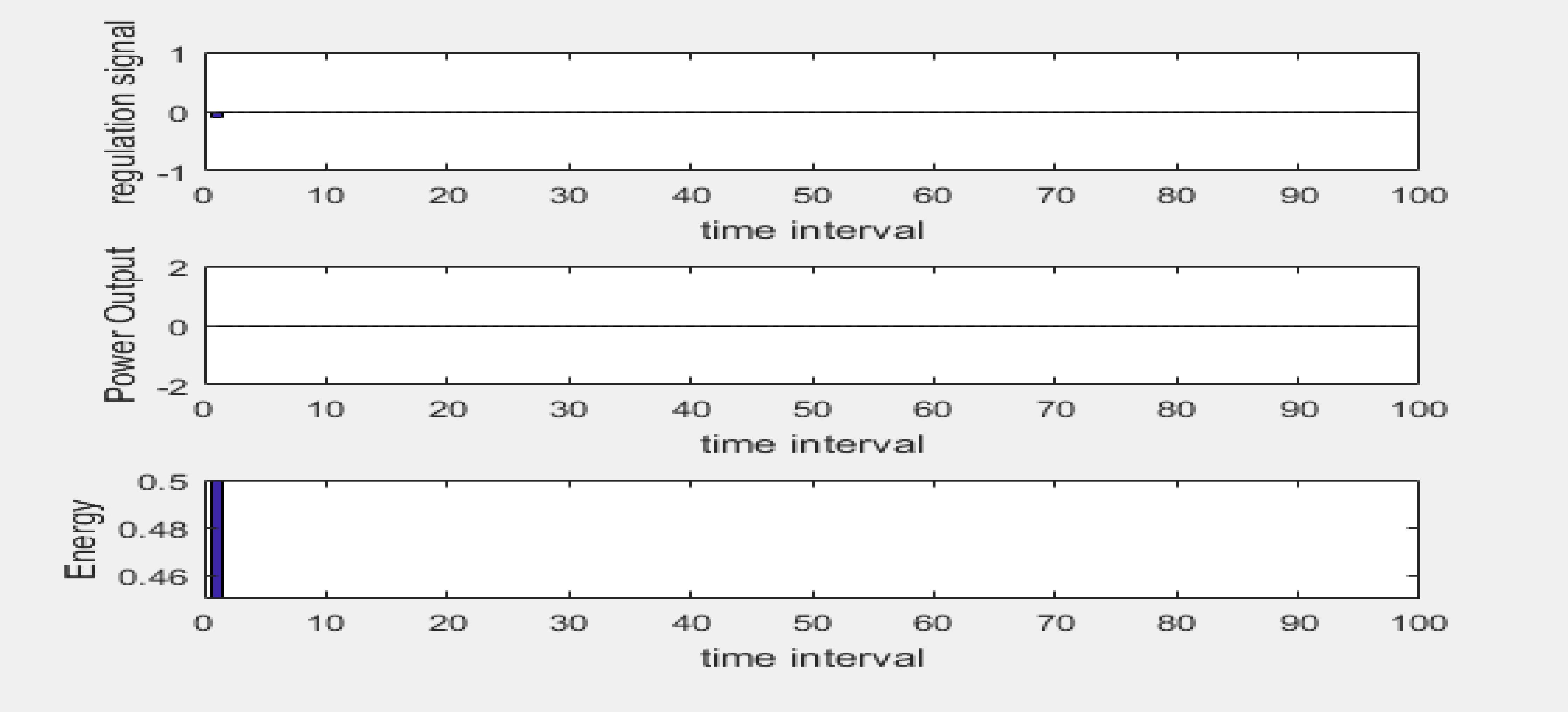
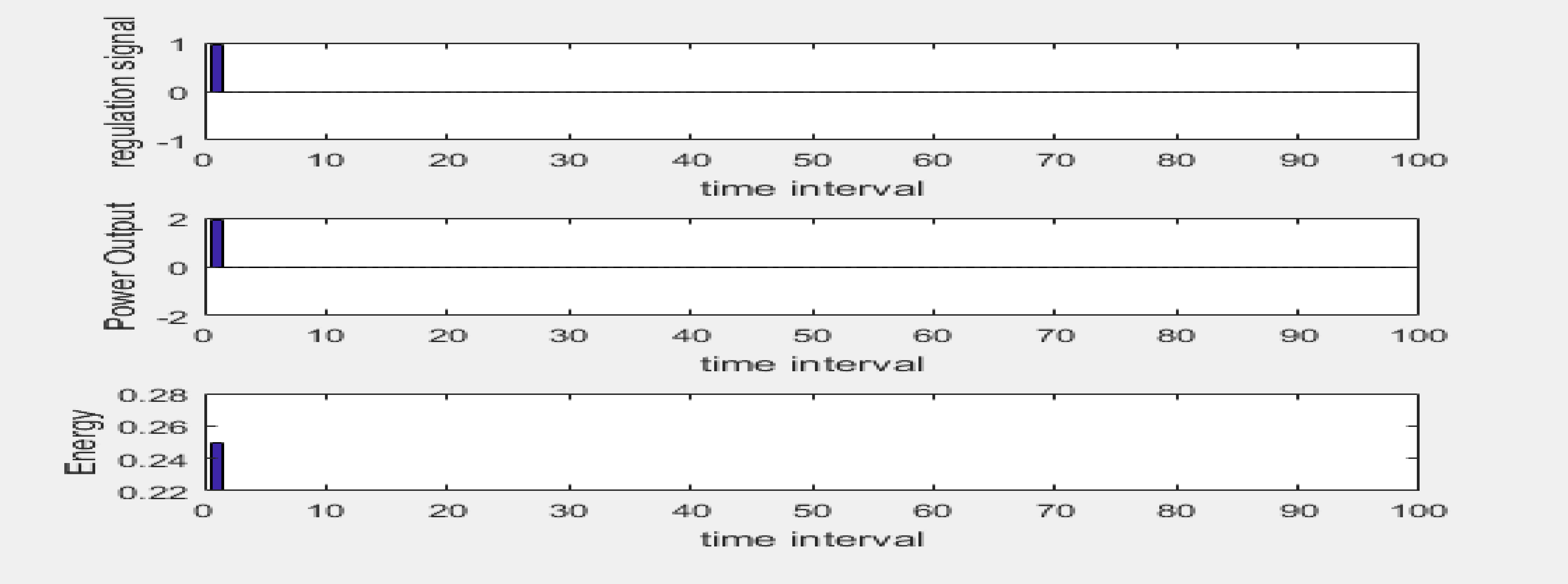
One directional service: Energy storage system only takes "up" signal when discharging, while only taking "down" signal when charging



Two Types of Services Mechanism

Two directional service: Energy storage system can take both “up” and “down” signal when possible.



Performance Criterion

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.

Simulation Setup

- 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

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Results Summary: Service Quality & Lifetime

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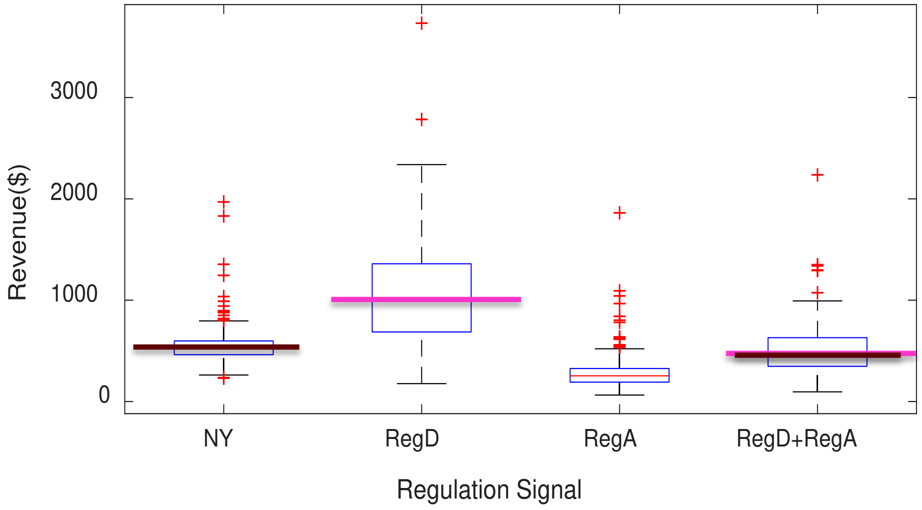
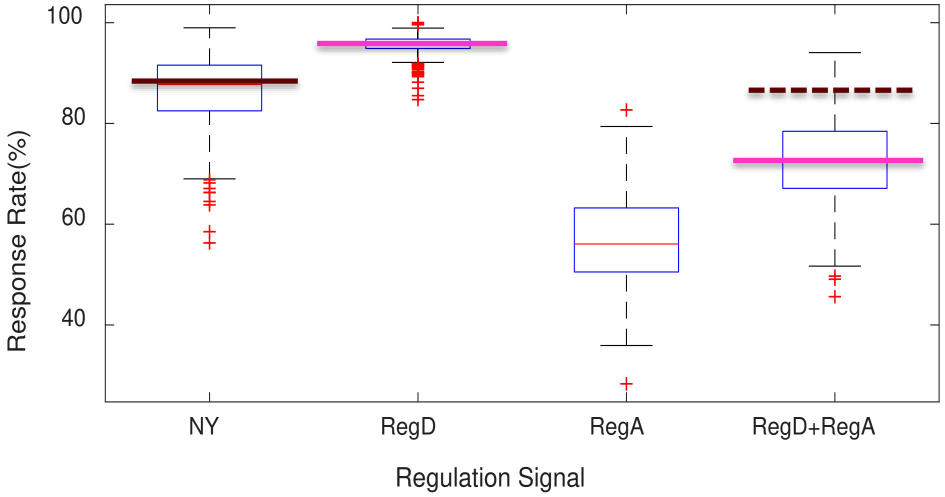
		PJM RegD		PJM RegA		NY-ISO	
		1-direction	2-direction	1-direction	2-direction	1-direction	2-direction
Battery	**Mileage (ΔMW/MW)**	133470	263210	20101	35472	87562	156450
	Response Rate(%)	**99.94**	**95.05**	99.91	55.7	99.92	85.46
	Estimate Lifetime(yrs)	4.72	3.89	5.93	4.23	5.28	3.99
Flywheel	**Mileage (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

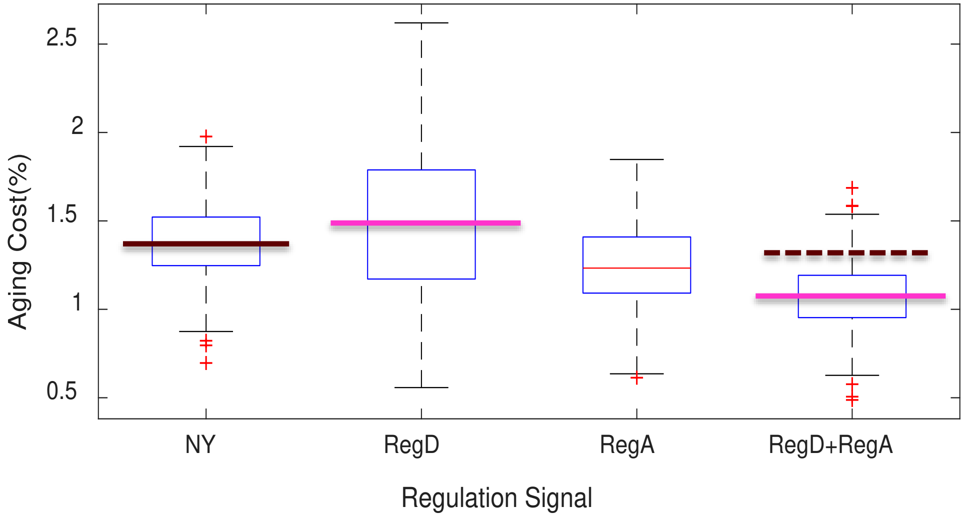
1. Regulation **signal design** makes a significant difference.
2. When providing regulation services, **battery lifetimes are shortened**.
3. When providing RegD services, battery lifetimes can be further shortened but not by much.
4. When providing 1-directional services, battery lifetimes can be prolonged.
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.



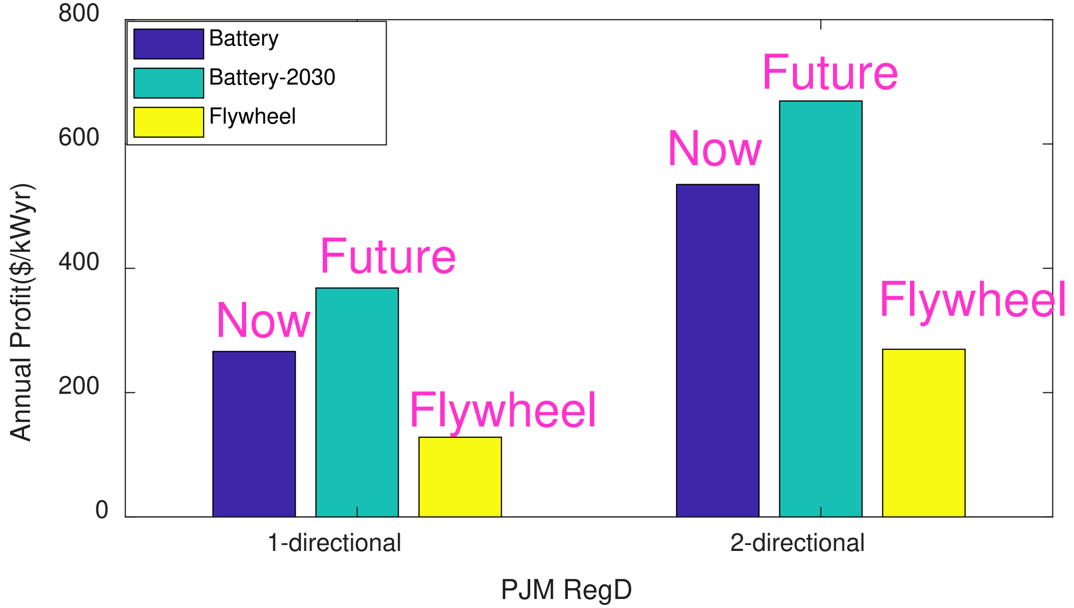
Comparison of daily revenue



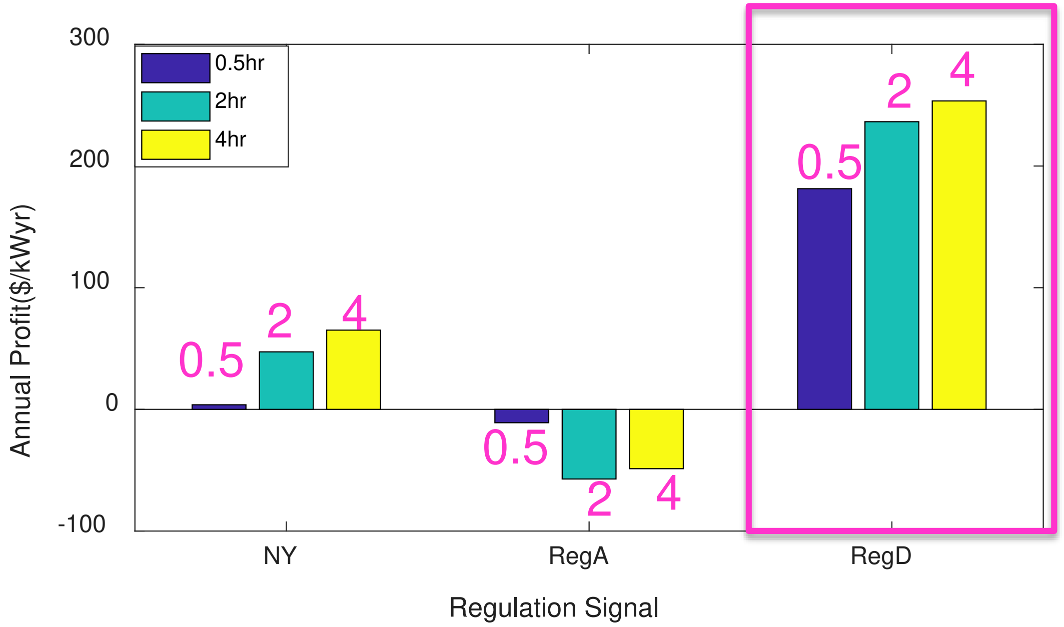
Comparison of daily response rate



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.

What are our next steps?

- 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

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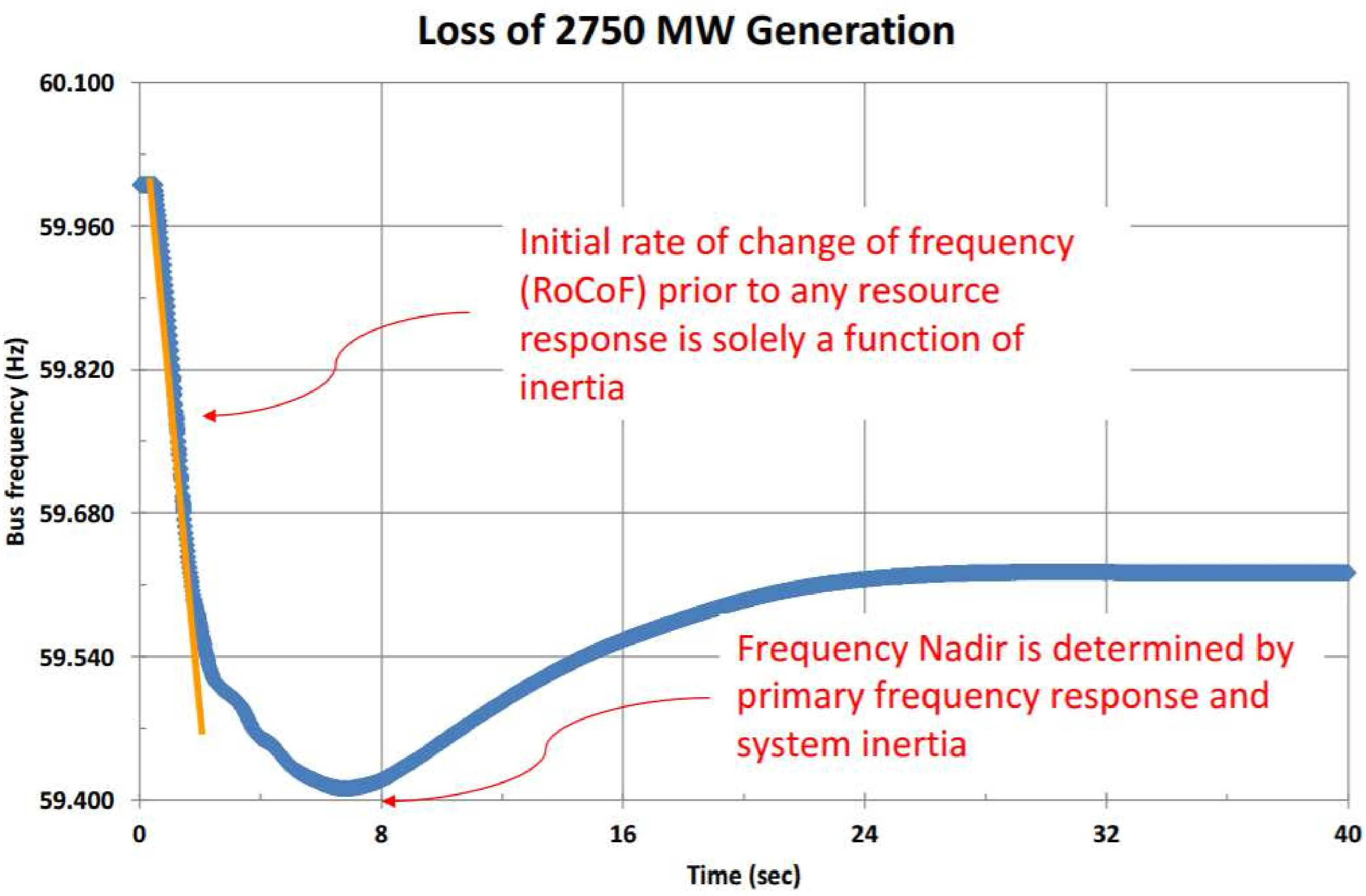
Part 5: Fast Frequency Response Services

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).

Frequency Response



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Primary Frequency Response

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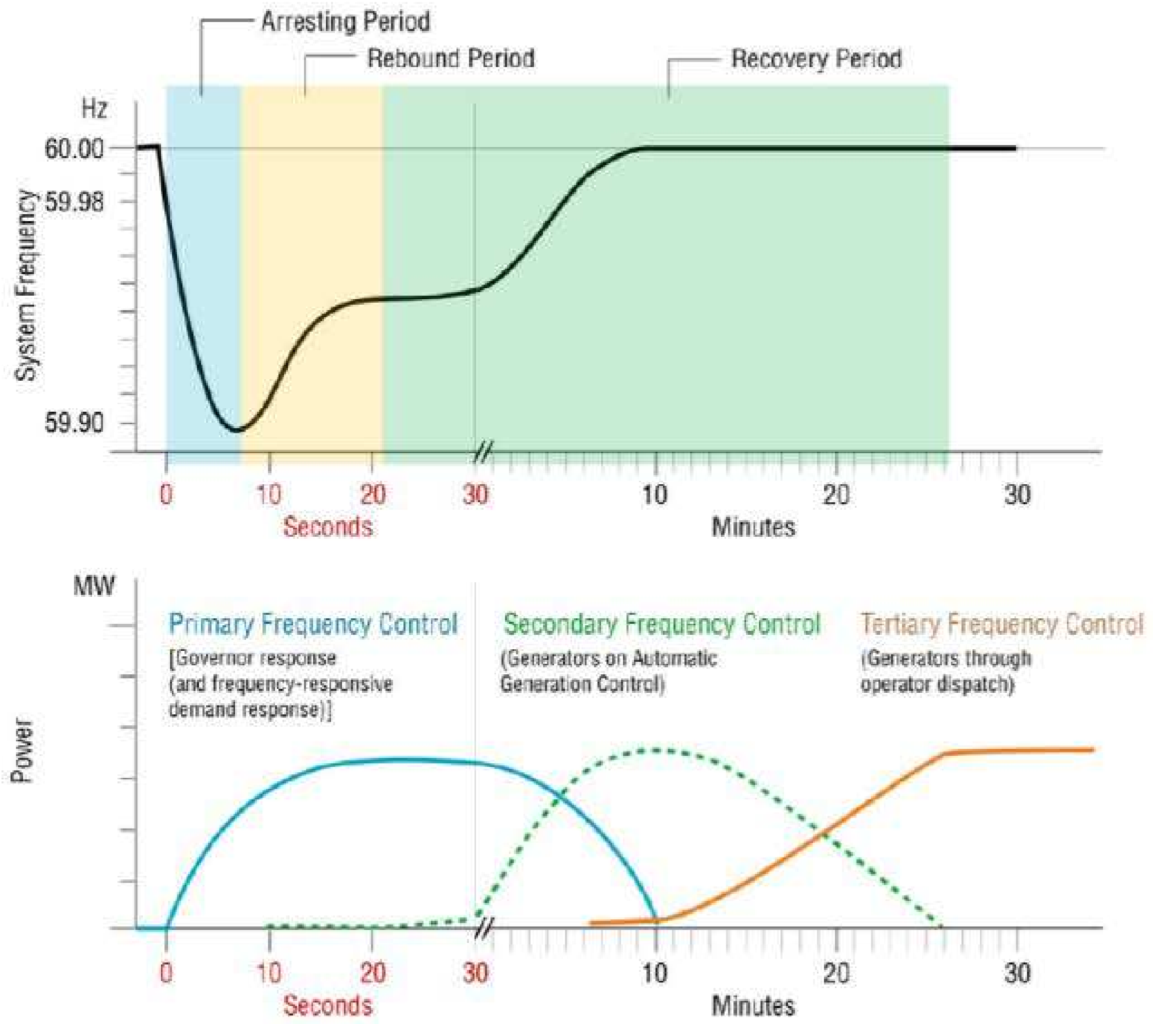
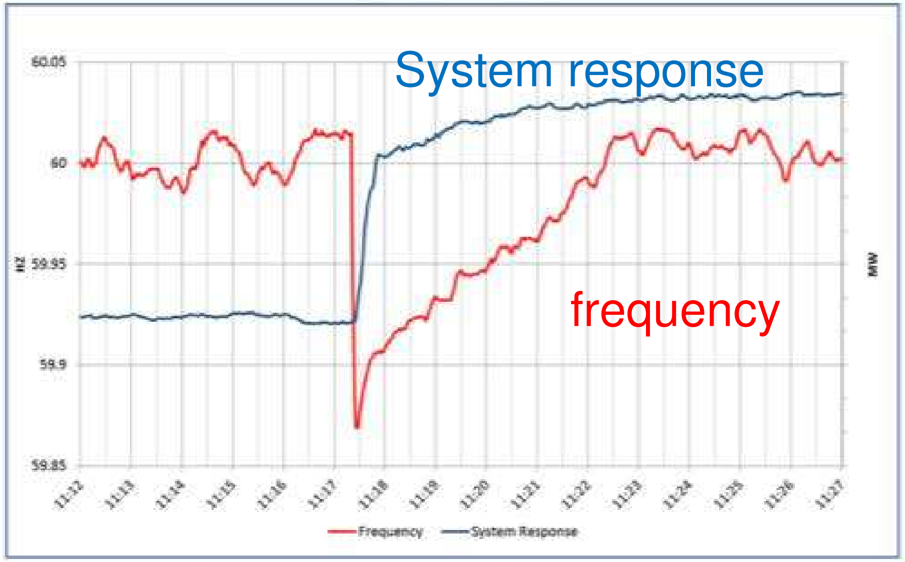
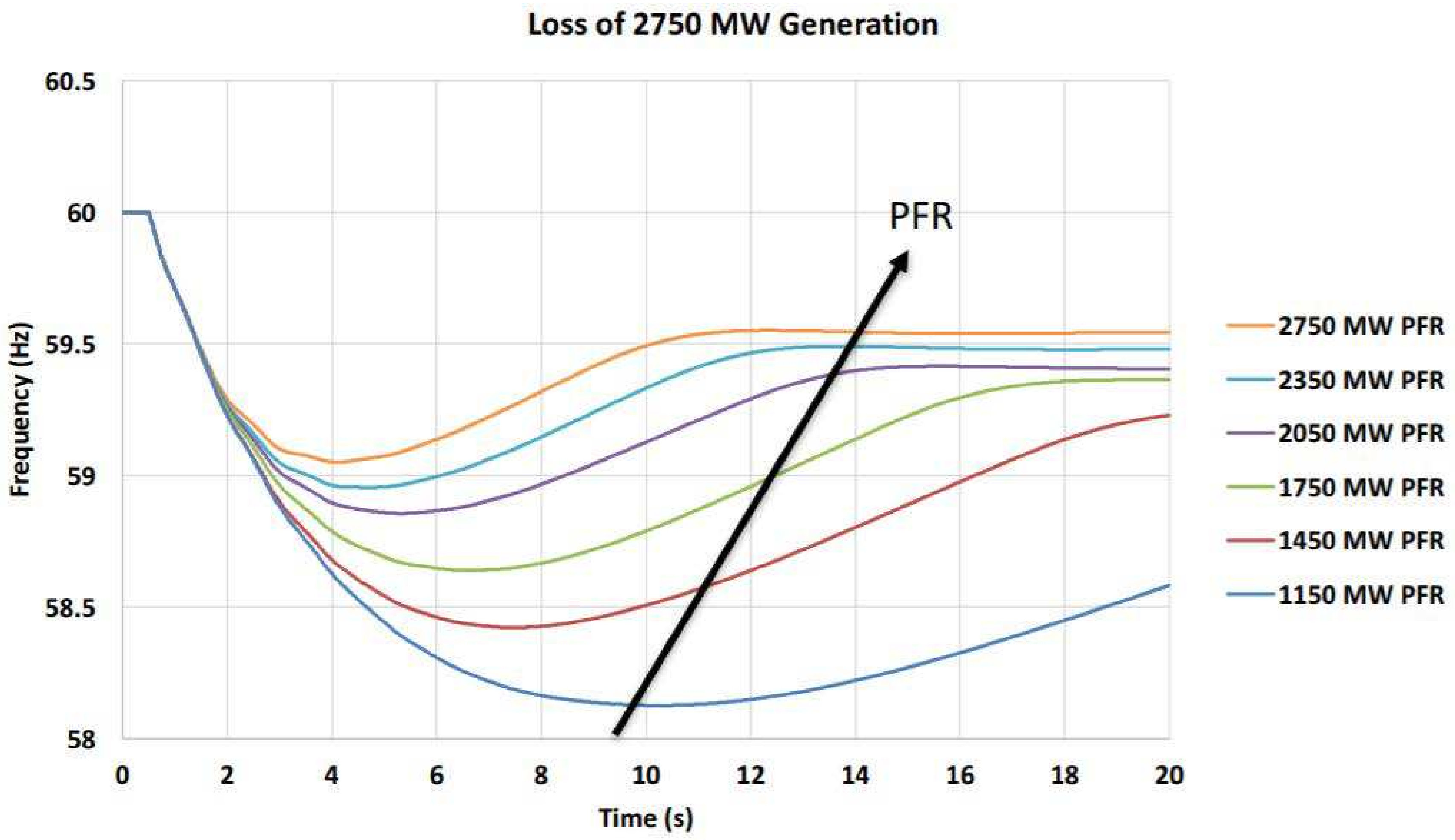


Actual System Response



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

PFR Impact on Frequency



More primary frequency response → less frequency drops and faster recovery

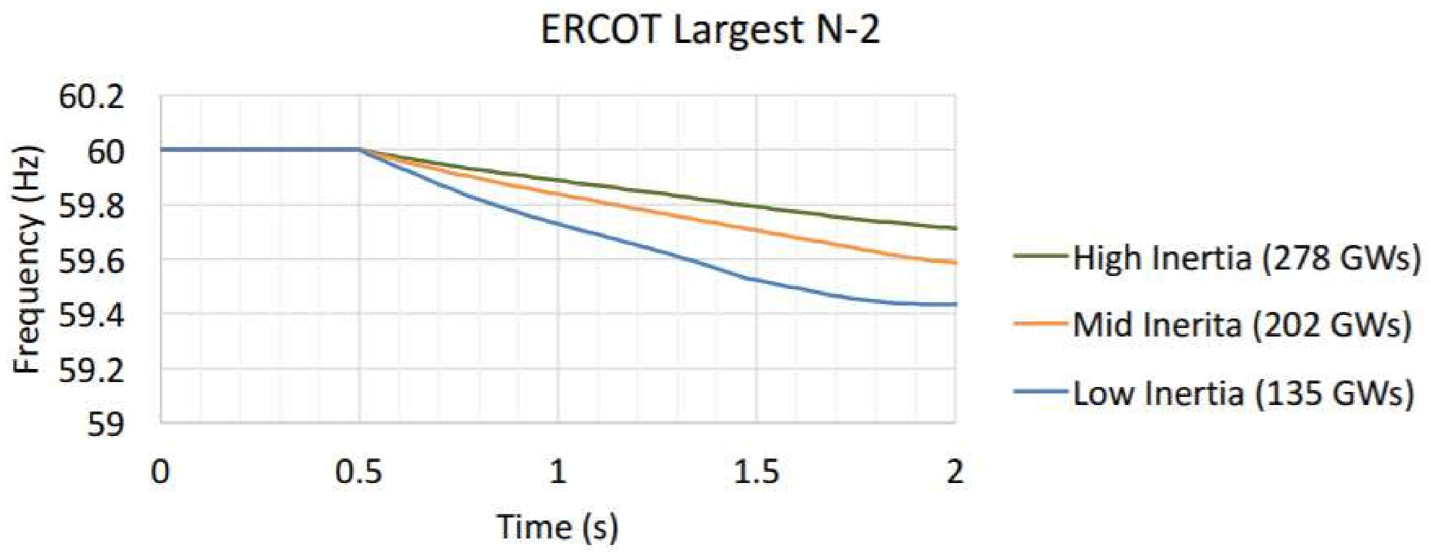
Inertia Definition

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

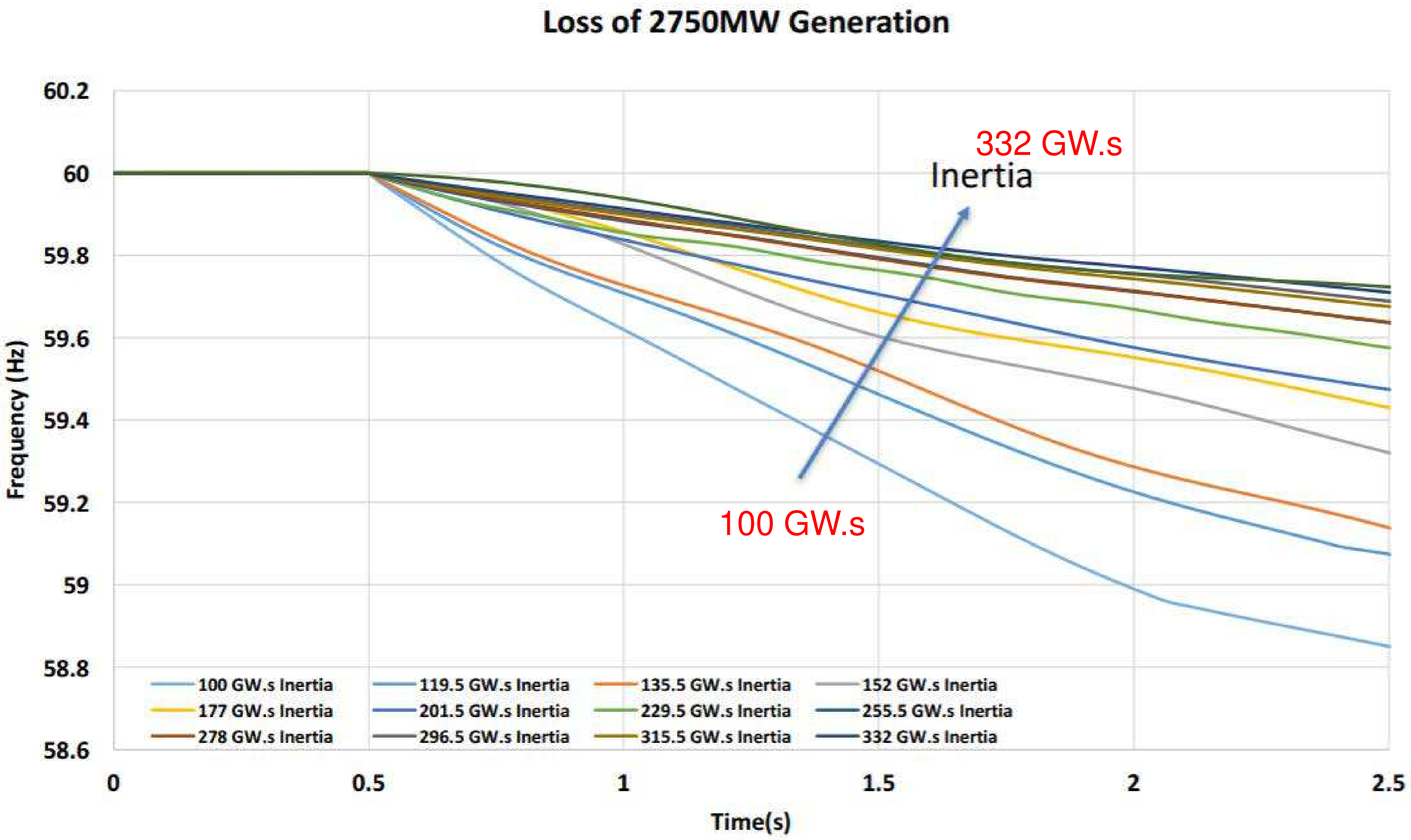
$$\frac{d\Delta f}{dt} = \frac{f_0}{2HS_B}(\Delta P_m - \Delta P_e)$$

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*



Inertia Impacts on Frequency



Declining Inertia

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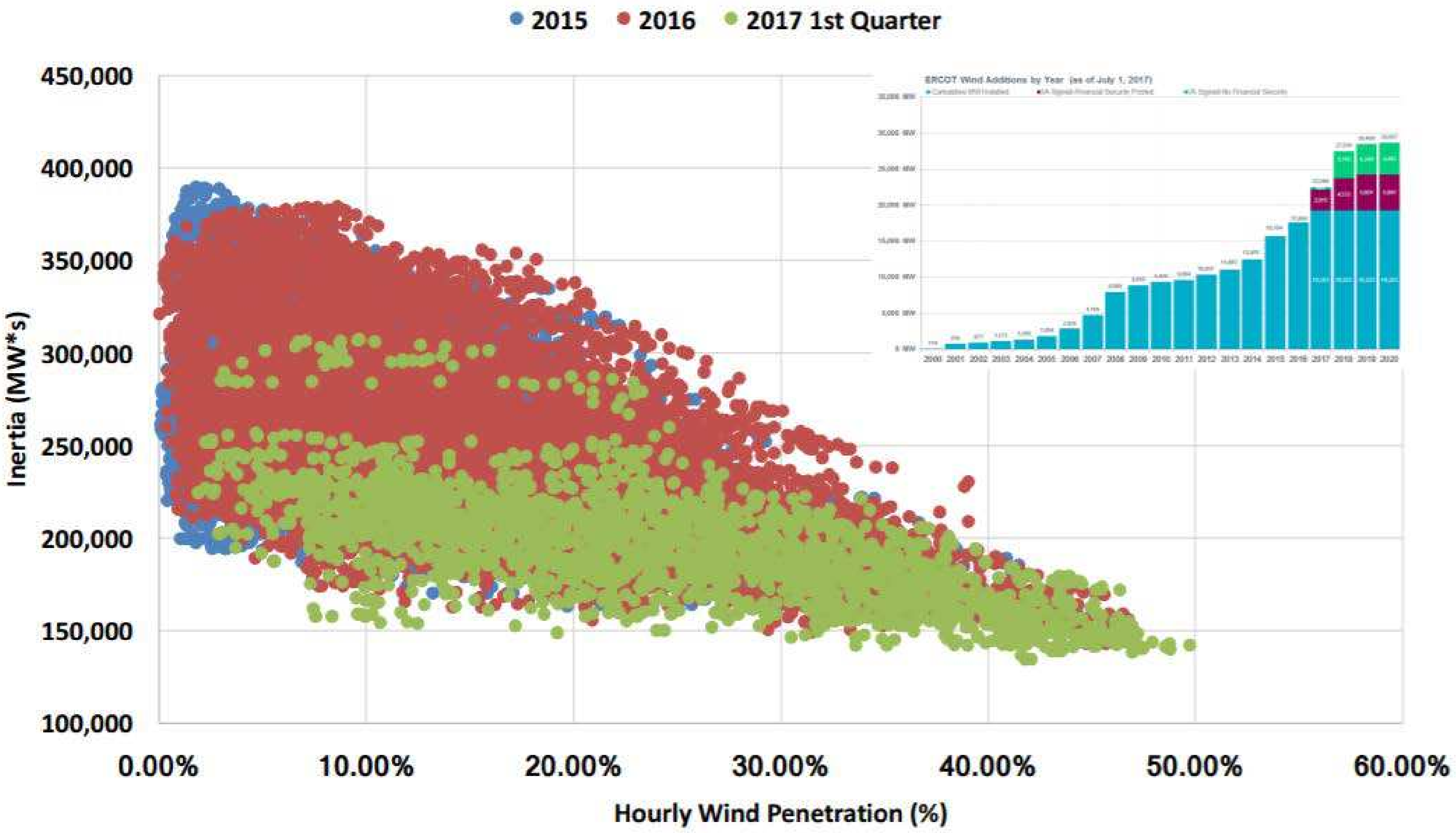


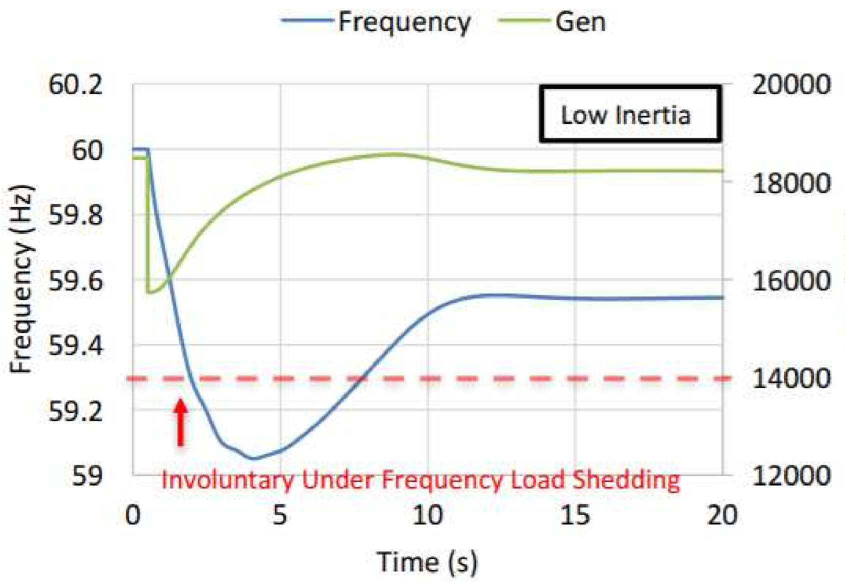
	2015	2016	2017 (1st Quarter)
Installed Wind Capacity	16,078 MW	18,564 MW	19,284 MW

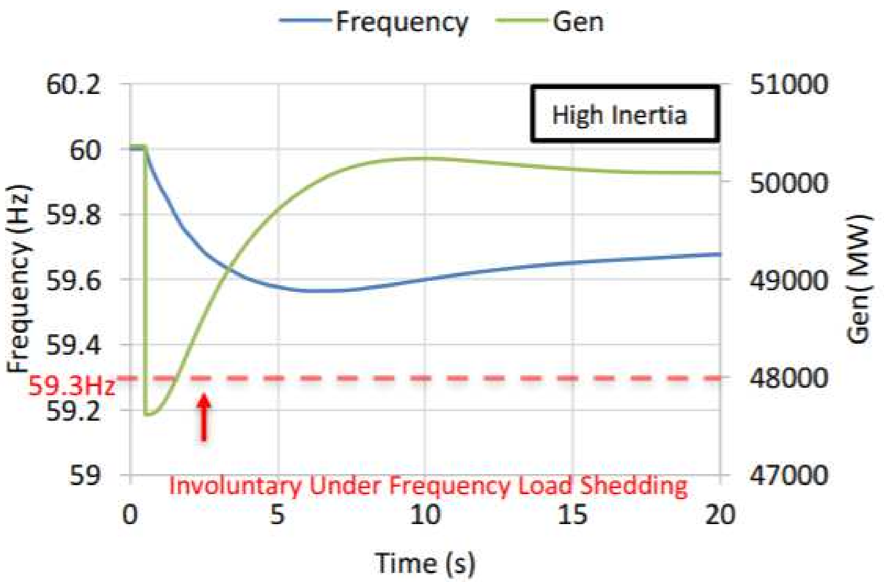
*Data Source: ERCOT Operations Data

Increasing Needs for Fast PFR

*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

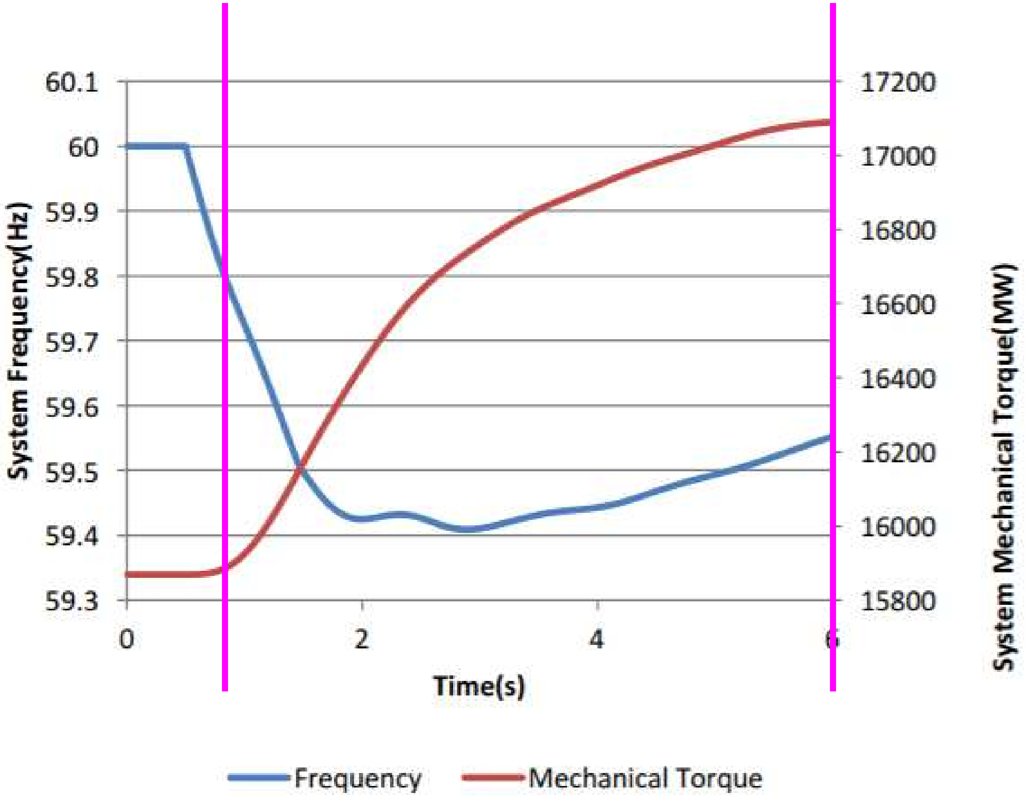
Comparison: PFR vs FFR

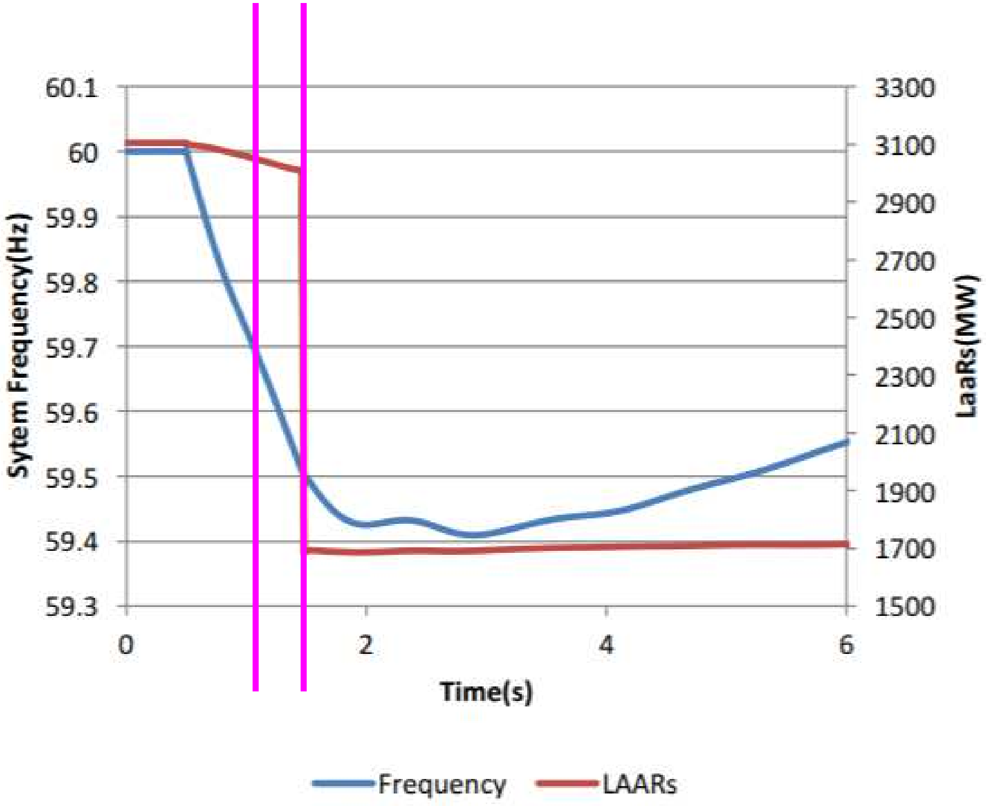
From Generators:

- **Delivered within 12 to 16 seconds**
- **From governor response**

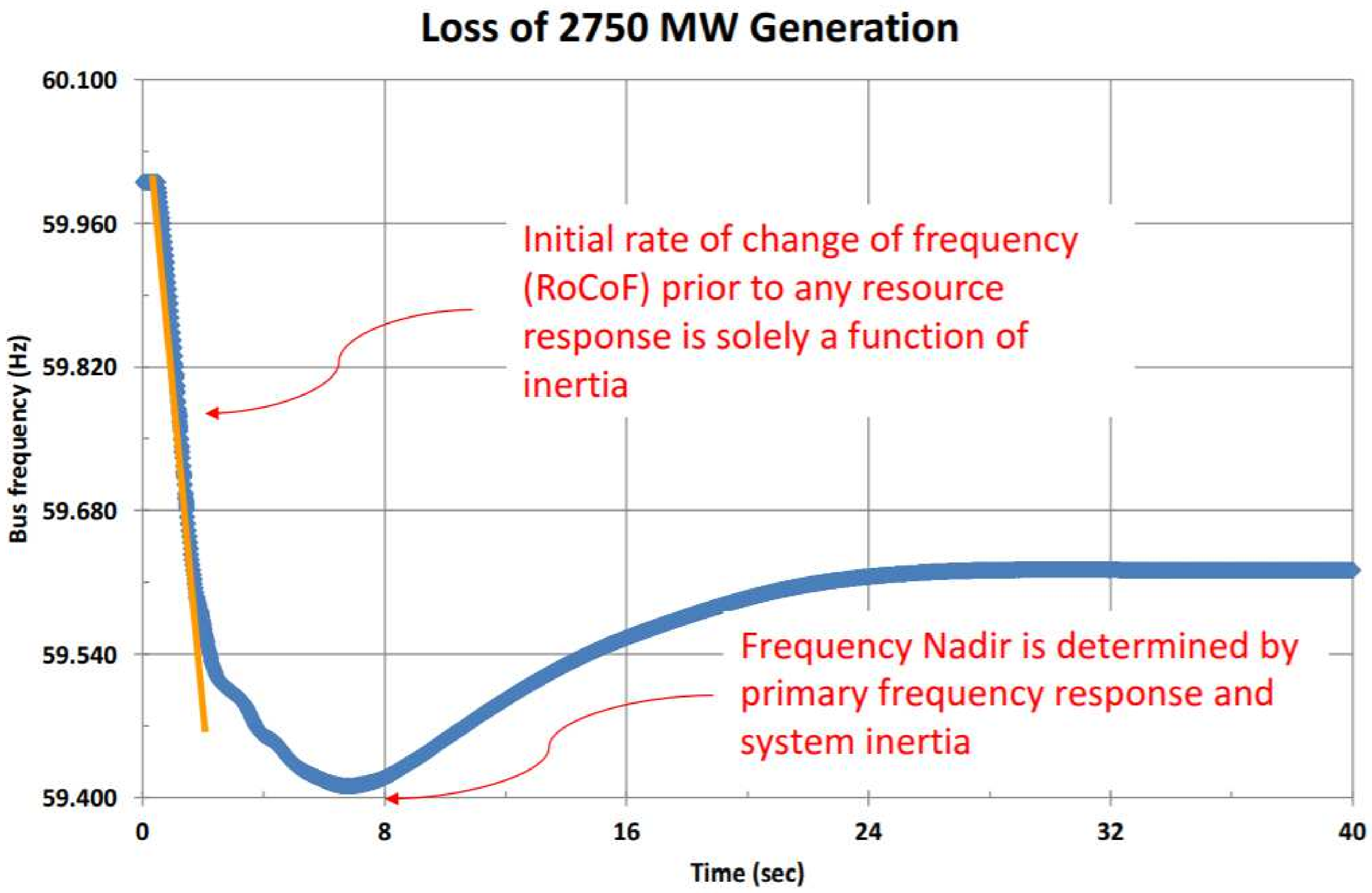
From Load/ other resources:

- **Delivered within 30 cycles (0.5 seconds)**
- **Triggered by under frequency relay (59.7Hz)**
- **Fast Frequency Response (FFR)**



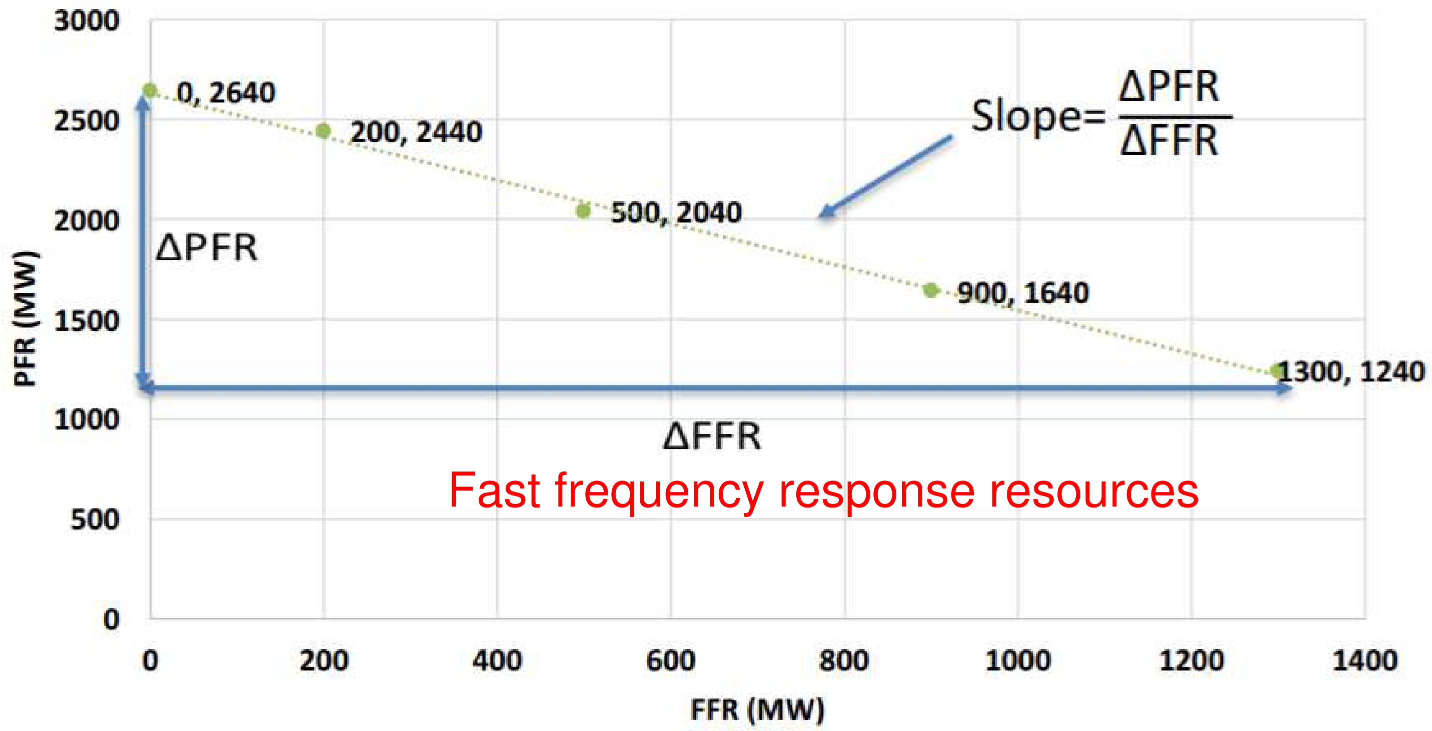


Frequency Response



Resource Equivalency

Primary frequency response resources



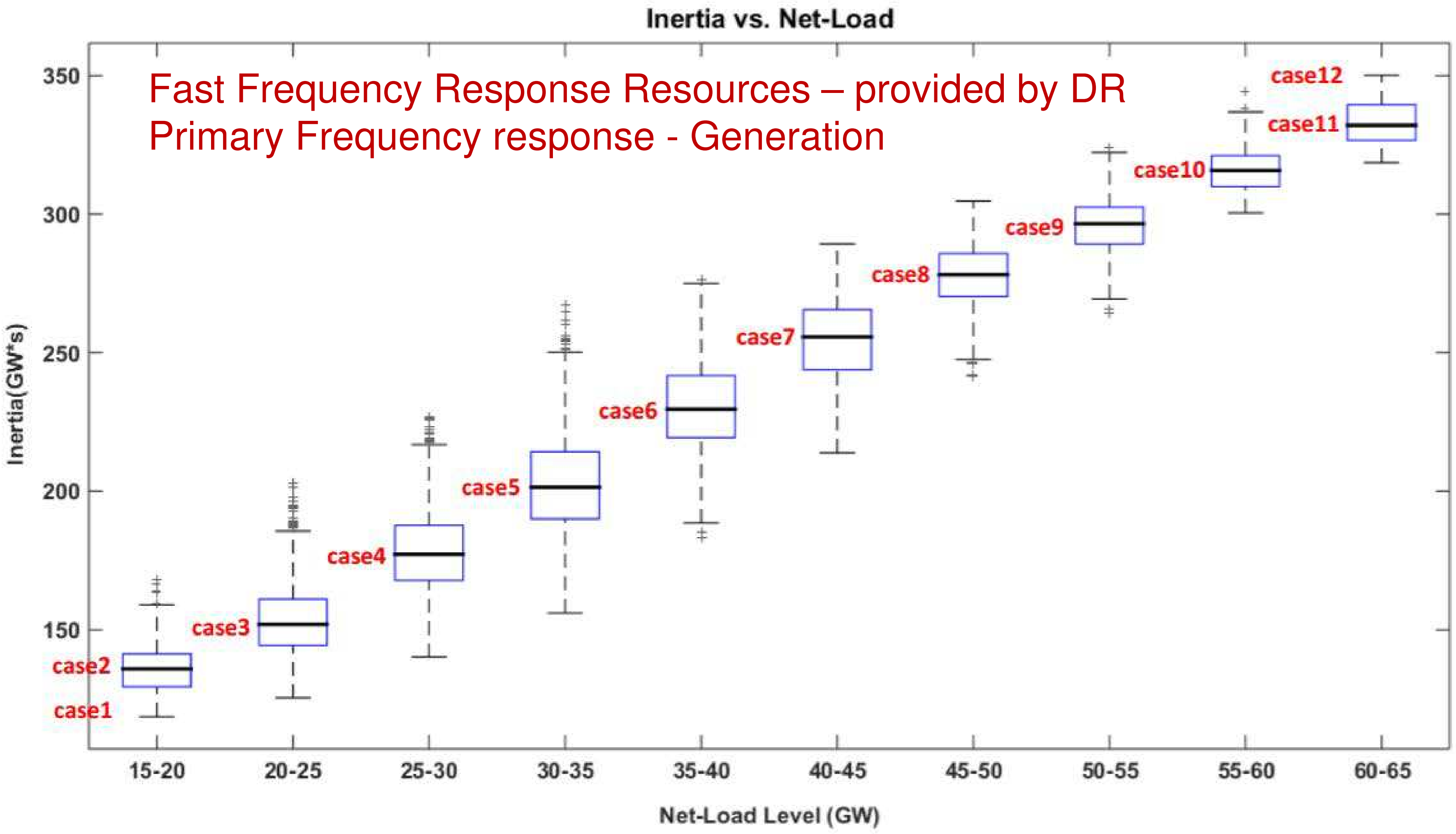
Fast frequency response resources

PFR/FFR Equivalency Ratio= - Slope= - $\frac{\Delta PFR}{\Delta FFR}$

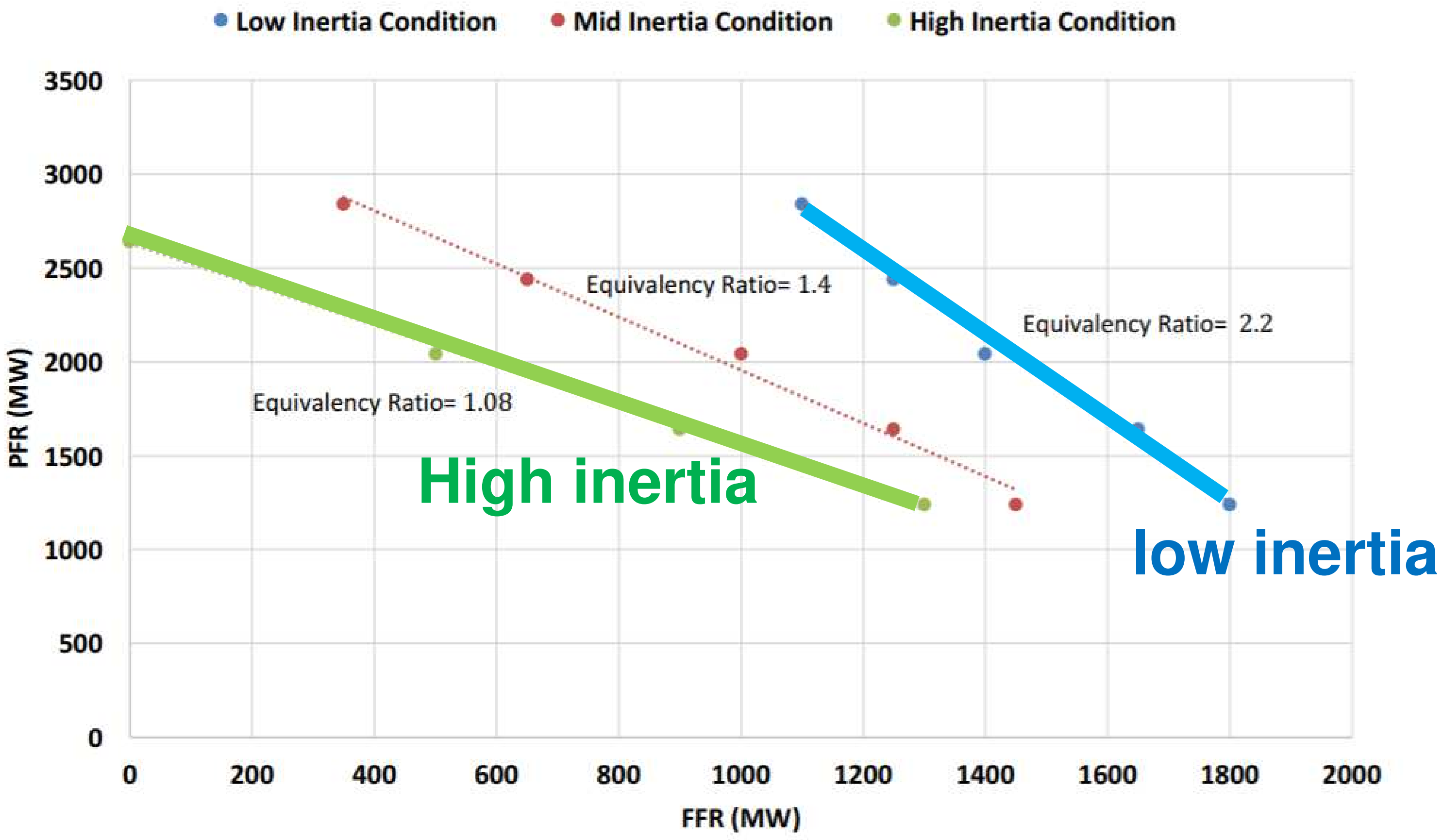
Interpretation: To replace 1MW of FFR, - $\frac{\Delta PFR}{\Delta FFR}$ MW of PFR is needed

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

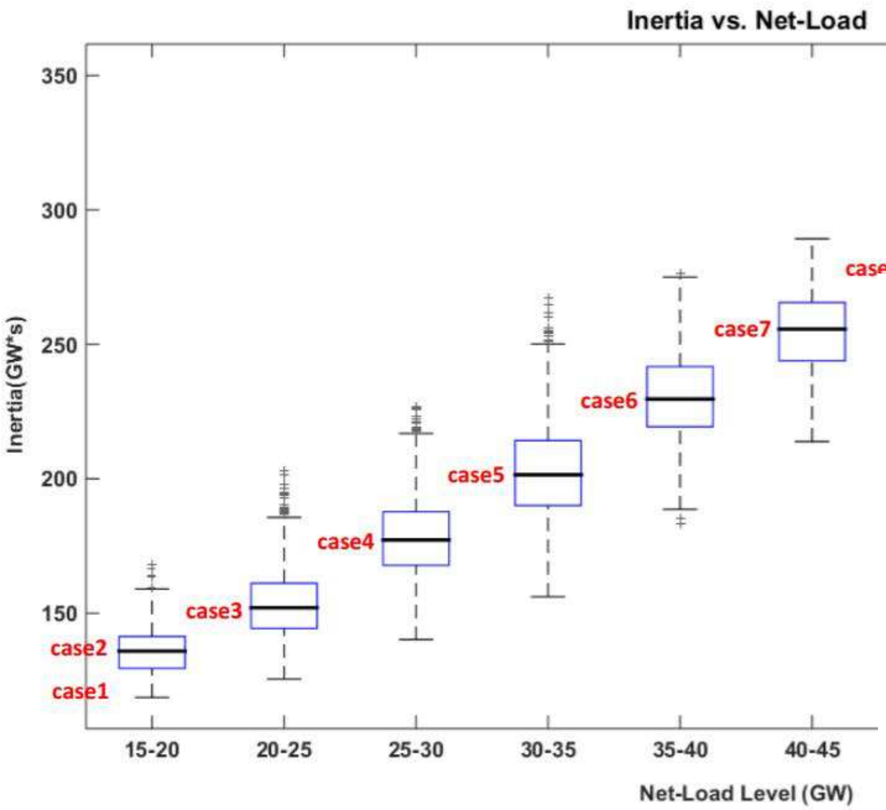
How to Address the FFR's Impact?



Equivalency Depends on Inertia



A Look-up Table

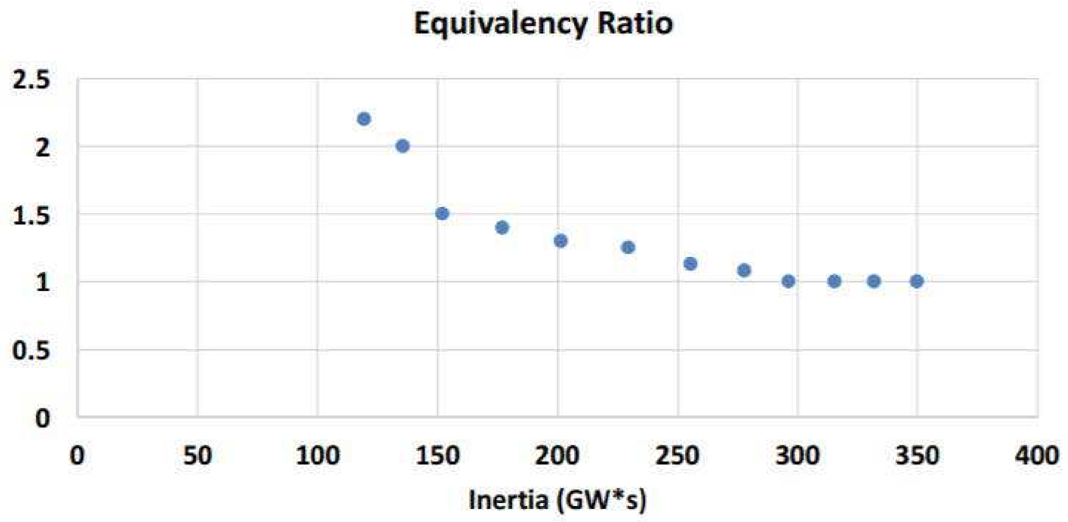


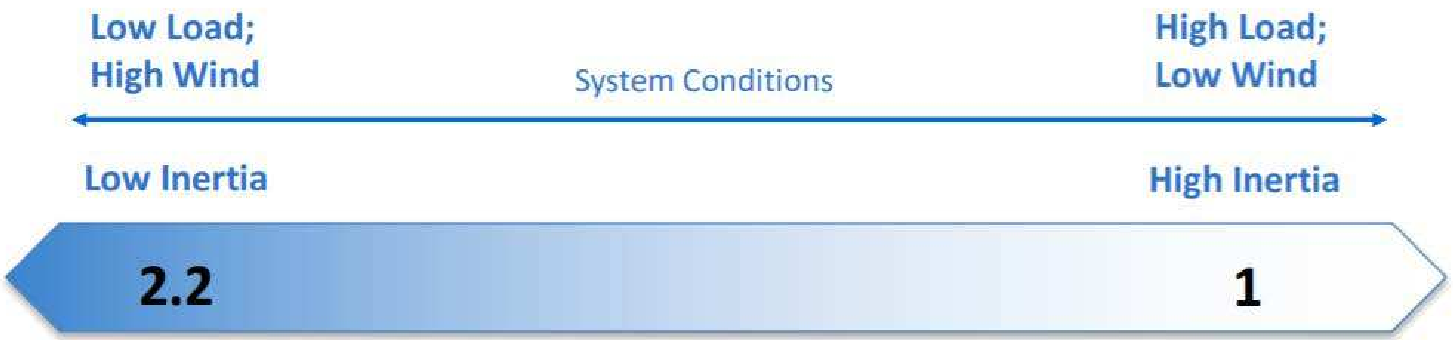
PFR Requirement Look-up Table

	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

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

Equivalency Ratio





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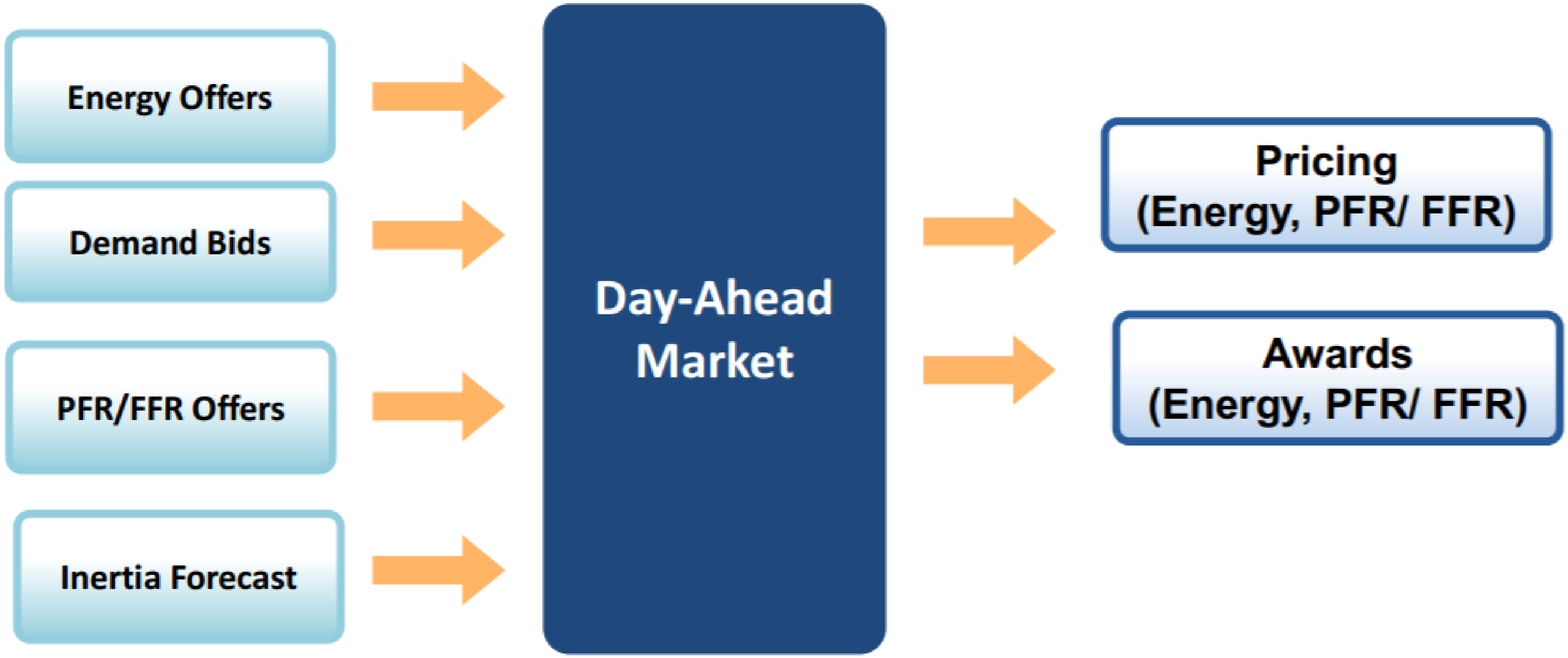
Part 5: Provision of Frequency Response Services

Reward Service based on Performance

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



Co-optimization of Energy and Ancillary

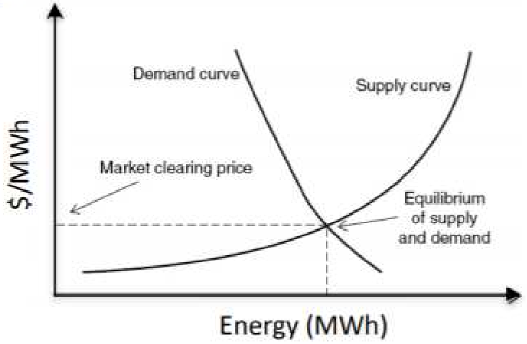
$$\max\{\underbrace{\sum_{j=1}^{Nd} b_j(d_j)}_{\text{Energy bid}} - \underbrace{\sum_{i=1}^{Ng} f_i(p_i)}_{\text{Energy offer}} - \underbrace{\sum_{i=1}^{Ng} f_i^{PFR}\left(p_i^{PFR}\right)}_{\text{PFR offer}} - \underbrace{\sum_{j=1}^{Nd} f_j^{FFR}\left(p_j^{PFR}\right)}_{\text{FFR offer}}\}$$

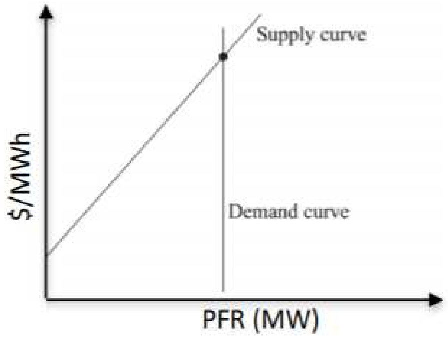
Variables:

- d_j Energy bid award for load *j* (MW)
- p_i Energy offer award for unit *i* (MW)
- p^{PFR}_i PFR award for unit *i* (MW)
- p^{FFR}_j 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).

Problem Formulation

Lagrange Function:

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

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

First-Order Necessary Conditions:

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

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

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

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

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

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

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

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

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

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

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

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PFR and FFR Equivalency

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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

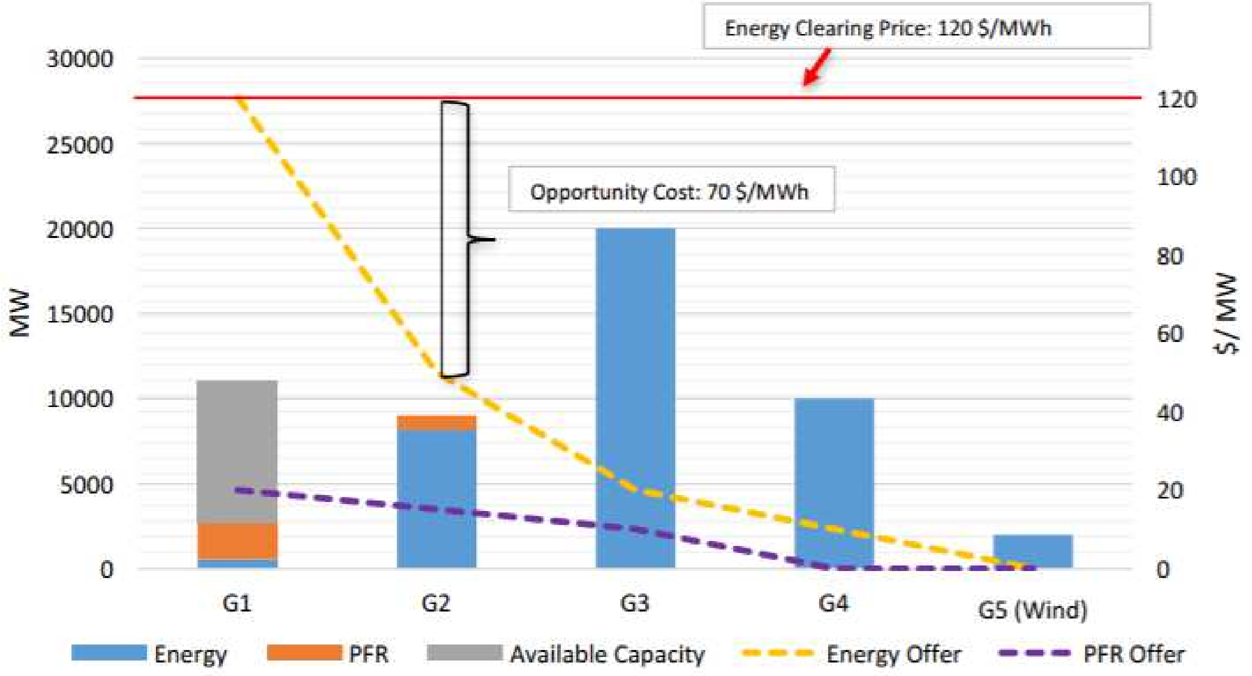
Eliminate price spikes

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	λ=120 ($/MWh)
PFR Clearing Price	α+β=85 ($/MW)
FFR Clearing Price	mβ=106.25 ($/MW)
λ, α, β	120,0,85

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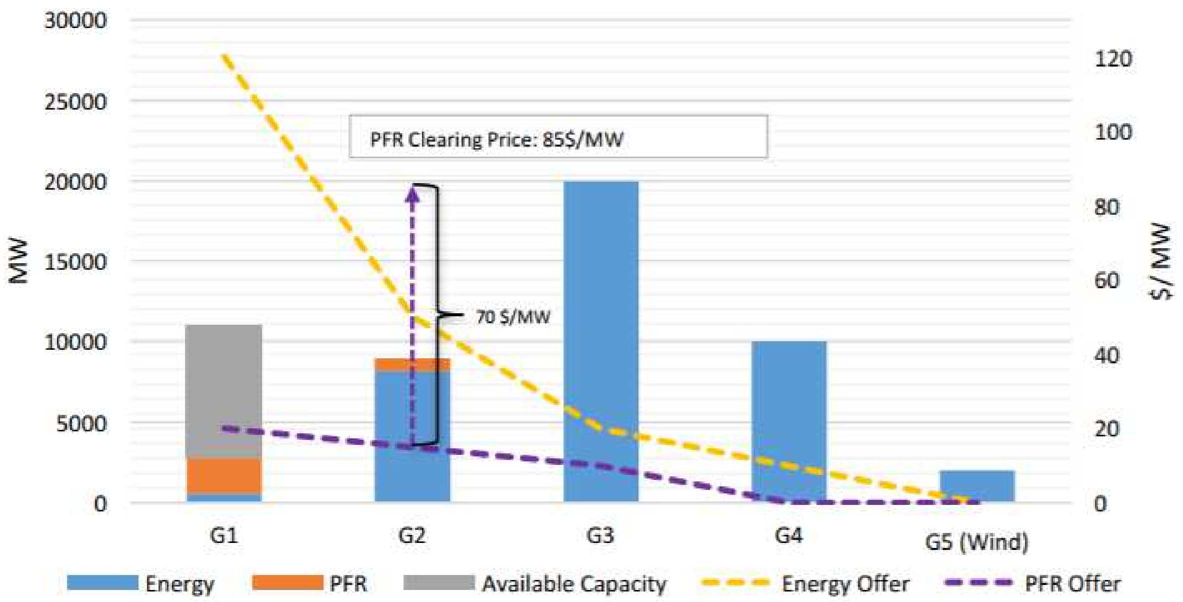
NO-FFR: Price Spikes in Both Market

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	λ=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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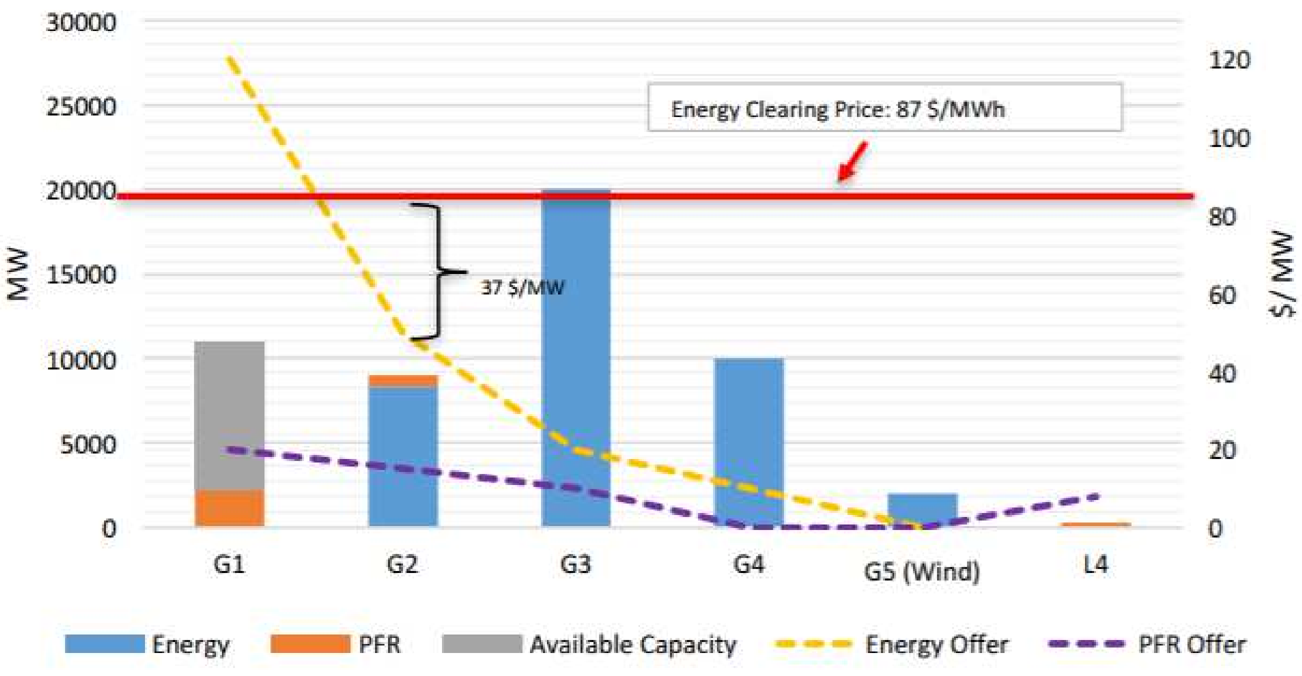
With FFR: Energy price may drop

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	λ=87 ($/MWh)
PFR Clearing Price	α+β=52 ($/MW)
FFR Clearing Price	mβ=65 ($/MW)
λ, α, β	87,0,52

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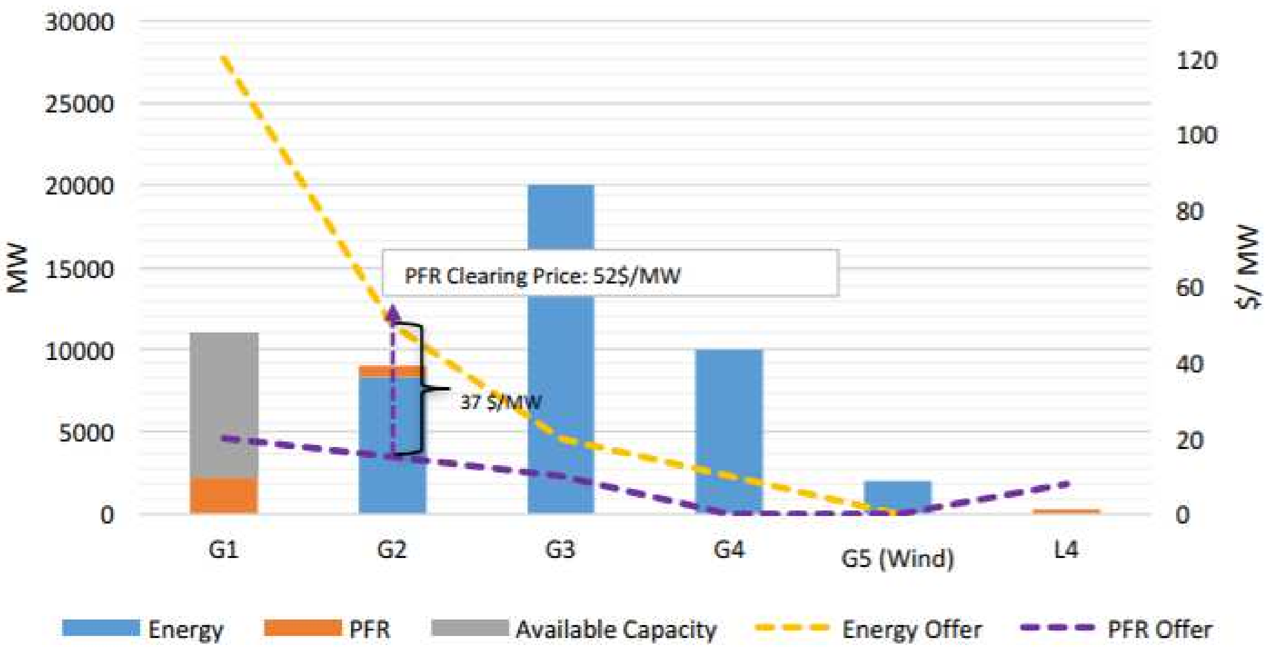
With FFR: PFR price will drop too

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	λ=87 ($/MWh)
PFR Clearing Price	α+β=52 ($/MW)
FFR Clearing Price	mβ=65 ($/MW)
λ, α, β	87,0,52

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Diminishing Mitigation Effects

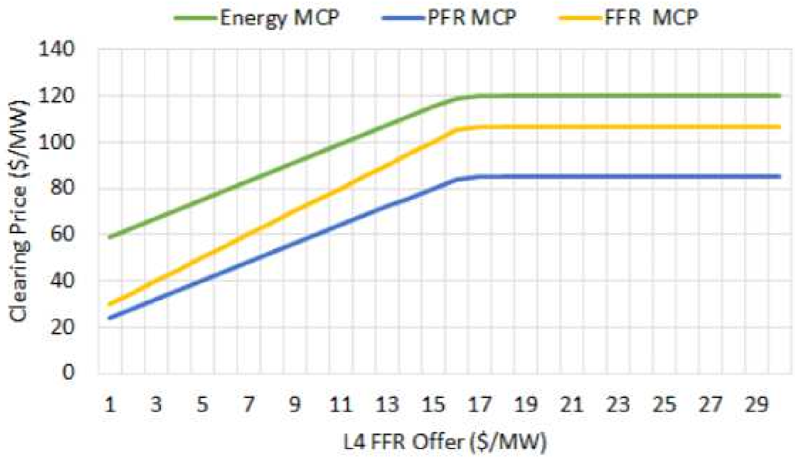
Assumed System Condition :

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.

Any Questions?