Towards Unified Operational Value Index of Energy Storage Services in Power Systems

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Motivation

Challenges with Renewable Generation

- Inter-temporal Variability
- Limited Predictability

Benefits of Explicit and Implicit Forms of Energy Storage Services

- Improve utilization of renewables
- Reduce energy imbalances and associated penalties
- Ancillary services such as regulation

Need to Understand Impact of Energy Storage

- Define unique features of heterogenous storage devices
- Pose the problem of analyzing impact of storage
- Assess the value of storage to power system operations

Need to quantify benefits of storage across power system operations using a **unified framework**.

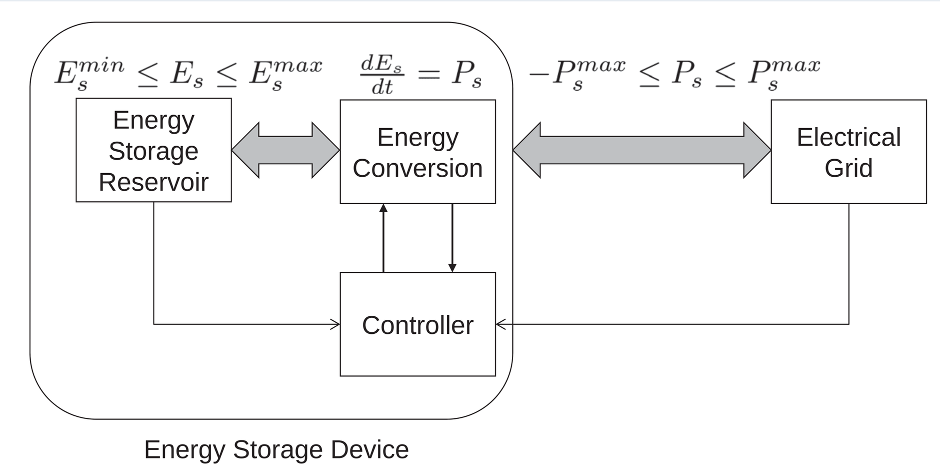
System Theoretical Perspective

Three major categories of energy conversion components are generators, loads, and energy storage

Energy Storage Module Definition [1]

- it lacks a primary energy source,
- $-P_s^{max} \leq P_s \leq P_s^{max}$, i.e., it can either deliver or draw power from the grid,
- $\frac{dE_s}{dt} = P_s$ is controllable, and
- $E_s^{min} \leq E_s \leq E_s^{max}$, i.e., it has a finite storage reservoir whose level is controllable.

Figure: Schematic of Energy Storage



Multi-time-scale Modeling

Table: Temporal decomposition

Control stage	Time scale	Assumption
Primary	Within seconds	Dynamics are locally stabilizable
Secondary (AGC)	10 s to minutes	Primary dynamics are already stabilized
Tertiary (ED, UC)	5 minutes to hours	Tie line flows and system frequency are at pre-specified values

Primary Control Model

Differential equations governing the dynamics of variable generator and storage combination are:

$$\dot{x}_v = f_v(x_v, x_v^{network}, u_v, u_v^{ref}) \quad (1)$$

$$\dot{x}^{network} = g(x) \quad (2)$$

$$\dot{x}_s = f_s(x_s, x_s^{network}, u_s(x_v), u_s^{ref}) \quad (3)$$

x_v	state variables of variable generator
$x_v^{network}$	interaction of generator with network
u_v	generator control variables
u_v^{ref}	generator controller set points
x_s	states of the storage unit
$x_s^{network}$	interactions of storage with network
u_s	storage control variables
u_s^{ref}	storage control set points

With *fast responding* energy storage the combined response from both modules could be improved [2].

Secondary Control Model

In Automatic Generation Control the governor reference is changed in response to frequency deviation:

$$\omega^{ref}[m] = \beta_S(\omega[m] - \omega[m-1]) \quad (4)$$

$$\Delta\omega[m] = \frac{1}{\beta_G + \beta_S + \beta_L} P_{imb}[m] \quad (5)$$

where β_i represents the droop characteristics of module i. Droop of energy conversion module i is defined as

$$\beta_i = \frac{\Delta\omega_i[m]}{\Delta P_i[m]}\Big|_{\Delta\omega_i^{ref}=0} \quad (6)$$

With the energy storage the overall system droop characteristic becomes $\beta = \beta_G + \beta_L + \beta_S$, where subscripts G, L, S represent aggregated generation, load, and storage, respectively. Thus energy storage can contribute to frequency regulation.

Tertiary Control Model

Energy storage can participate in load following and load leveling. Power absorbed or delivered by the energy storage unit $P_s[K]$, is the decision variable. Ramping rate is R_s

$$P_s^{min} \leq P_s[K] \leq P_s^{max} \quad (7)$$

$$E_s[K] = E_s[K-1] - \eta P_s[K-1] \quad (8)$$

$$0 \leq E_s[K] \leq E_s^{max} \quad (9)$$

$$|P_s[K] - P_s[K-1]| \leq R_s \quad (10)$$

Operational Value of Energy Storage

- Different types of storage devices can participate at different time scales in the control action, depending upon their inherent characteristics such as power rating, energy capacity, droop, ramping etc.
- Participation in multiple control actions has potential for higher profits for storage service providers
- Contribution by storage can reduce system cost for balancing actions

Unified Operational Value Index

Proposed operational value index considers multiple revenue streams: energy, regulation, spinning reserve and benefits from deferral of system upgrades attributed to the energy storage device.

$$V_s = \frac{\sum_{k=1}^{N}(\lambda^e[k]P_s(k) + \lambda^{ru}P_s^{ru}(k) + \lambda^{rd}P_s^{rd}(k) + \lambda^{sr}P_s^{sr}(k)) + PV_d}{T.P_s^{max}} \quad (11)$$

For this case study we consider only the operational value in ISO market operations.

Decision Making Framework

The decision of the extent of storage participation in markets can be formulated as a *co-optimization* problem based on forecast of prices. The following expected value problem is solved, with the objective of profit maximization [3].

$$\max_{\vec{P}_s(k), \vec{P}_s^{ru}(k), \vec{P}_s^{rd}(k), \vec{P}_s^{sr}(k)} \mathrm{E}[\sum_{k=1}^{N}\{\hat{\lambda}^e(k)P_s(k) + \hat{\lambda}^{ru}(k)P_s^{ru}(k) + \hat{\lambda}^{rd}(k)P_s^{rd}(k) + \hat{\lambda}^{sr}(k)P_s^{sr}(k) - C(k)(P_s(k))^2\}] \quad (12)$$

s.t.

$$E_s(k) = E_s(k-1) - [P_s(k) - \eta_c P_s^{rd}(k) + \frac{1}{\eta_d}P_s^{ru}(k)].\Delta t \quad (13)$$

$$P_s(k) + P_s^{ru}(k) + P_s^{sr}(k) \leq P_s^{max}(k) \quad (14)$$

$$P_s^{rd}(k) \leq P_s(k-1) + P_s^{max}(k) \quad (15)$$

$$E_s^{min} \leq E_s(k) \leq E_s^{max} \quad (16)$$

$$-P_s^{max} \leq P_s(k) \leq P_s^{max} \quad (17)$$

$$P_s(k) - P_s(k-1) \leq R_s \quad (18)$$

$$P_s^{ru}(k) \geq 0 \quad (19)$$

$$P_s^{rd}(k) \geq 0 \quad (20)$$

$$P_s^{sr}(k) \geq 0 \quad (21)$$

Nomenclature

P_s^{max}	Maximum charging/discharging power (MW)
E_s^{max}	Maximum energy storage level (MWh)
E_s^{min}	Minimum energy storage level (MWh)
R_s	Ramp rate of storage
η_s	Roundtrip efficiency of the storage device
N	Number of time periods
Δt	Duration of time periods
$E_s(k)$	Energy storage level of device
$\hat{\lambda}^e(k)$	Forecast energy market price ($/MWh)
$\hat{\lambda}^{ru}(k)$	Forecast regulation up capacity price ($/MW)
$\hat{\lambda}^{rd}(k)$	Forecast regulation down capacity price ($/MW)
$\hat{\lambda}^{sr}(k)$	Forecast spinning reserve capacity price ($/MW)
$C_s(k)$	Charging/discharging cost of energy storage
$P_s(k)$	Energy sold/purchased by storage (MWh)
$P_s^{ru}(k)$	Regulation up capacity sold (MW)
$P_s^{rd}(k)$	Regulation down capacity sold (MW)
$P_s^{sr}(k)$	Spinning reserve capacity sold (MW)

Case Study

Figure: Modified IEEE RTS 24 bus system

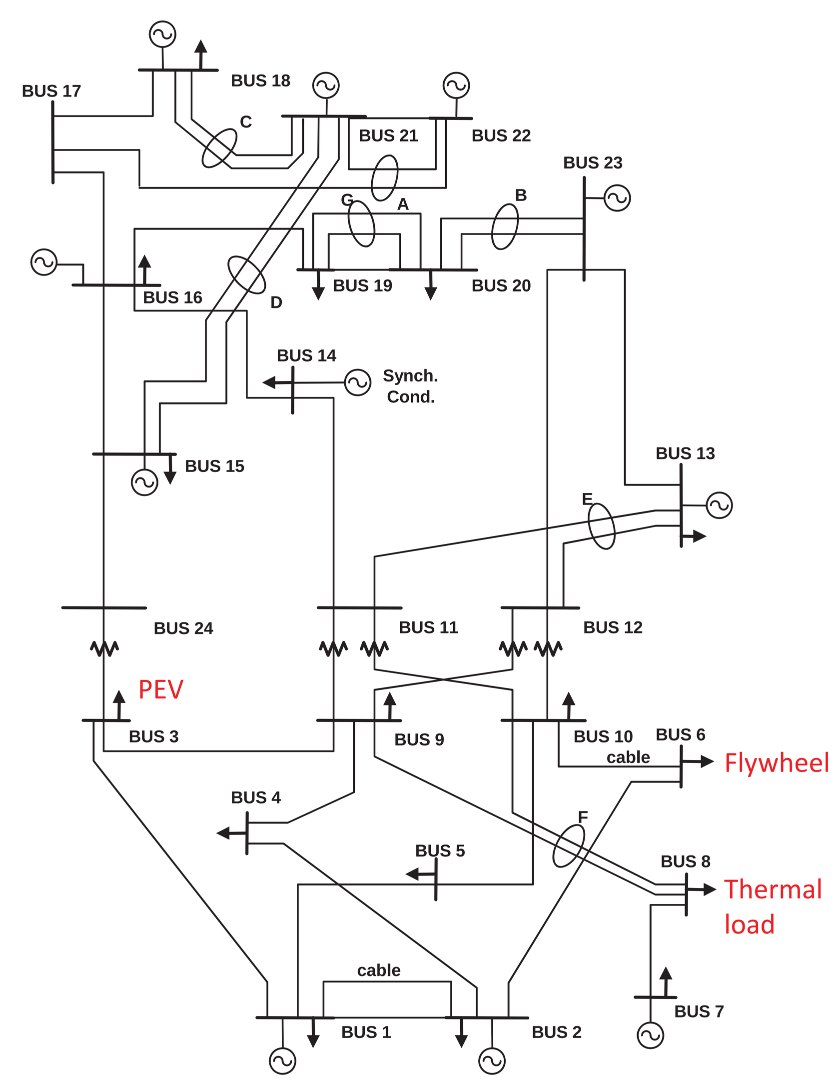


Table: Storage Technologies and Applications

Technology	Energy	Regulation	Spinning Reserve
Flywheel	No	Yes	No
PEV	Yes	Yes	No
Thermal Load	Yes	No	Yes

Thermal Load Model

Using smart controls that act in response to price signals, thermal loads such as air-conditioning can act as analogues to energy storage. The model for power consumption is:

$$T^{in}(k+1) = \epsilon T^{in}(k) + (1-\epsilon)(T^{out}(k) - \eta_{cop}\frac{P(k)}{A}) \quad (22)$$

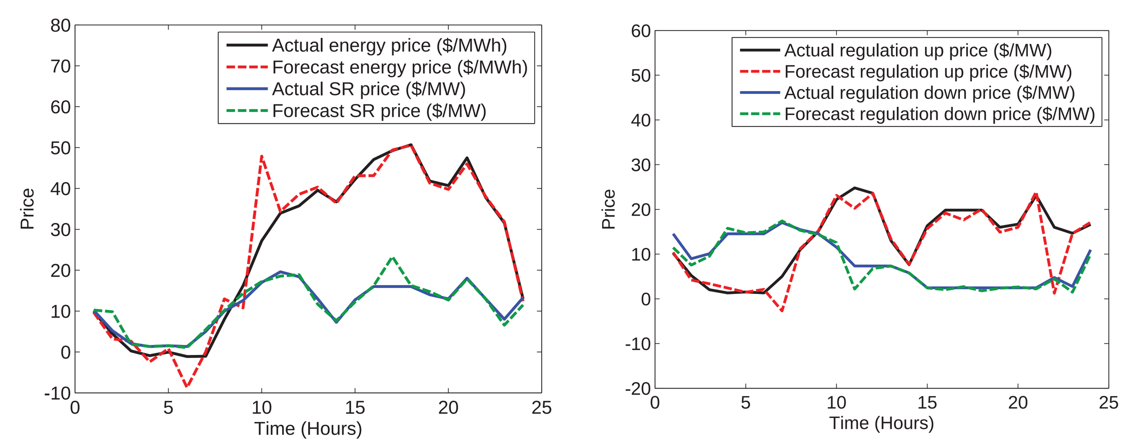
$T^{in}(k)$ = inside temperature in period k,
$T^{out}(k)$ = outside temperature in period k,
$P(k)$ = power consumption in period k,
η_{cop} = coefficient of performance of cooling system = 2.5,
τ = duration of control periods = 1 hour,
TC = time constant of system = 2.5 hours,
$\epsilon = exp[-\tau/TC]$ = factor of inertia,
A = overall thermal conductivity = 0.14 $kW/^{\circ}F$
$T^{min} \leq T^{in}(k) \leq T^{max}, \forall k$.

Smart controls reduce power consumption while maintaining inside temperature within preset limits.

Day Ahead Market Simulation

Figure: Forecast and Actual Day-Ahead Market Prices

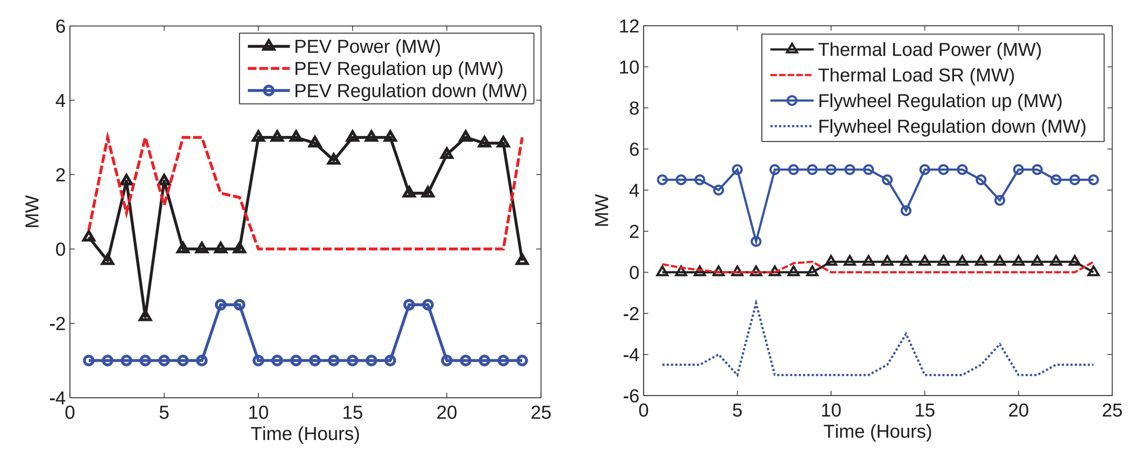
(a) Energy and Reserve Prices (b) Flywheel and Thermal Load



Results

Figure: Storage participation in Day-Ahead Market

(a) PEV (b) Flywheel and Thermal Load



Storage decisions based on forecast prices, revenue on actual prices. Average results for 1000 Monte Carlo runs are:

Table: Day-Ahead Market Revenue ($/MW)

Technology	Energy	Regulation	Spinning Reserve
Flywheel	-	120.30	-
PEV	495.97	226.95	-
Thermal Load	63.61	-	3.21

Hourly market constrains participation of flywheels. Short duration market would realize full potential of such fast responding storage devices.

Conclusions

- **Unified operational value index** - first step for assessment of benefits of energy storage across different technologies and market designs
- Cross-market co-optimization model - **decision making tool** for energy storage service providers
- **Distributed energy storage** can improve system flexibility by providing ancillary services

Future Work

- Empirical study of proposed framework using real world data
- Regulatory and pricing mechanism design for distributed storage

References

[1] L. Xie, A. A. Thatte, and Y. Gu, "Multi-time-scale modeling and analysis of energy storage in power system operations," in *Proc. IEEE Energytech*, Cleveland, OH, May 25-26, 2011, pp. 1–6.

[2] A. A. Thatte, F. Zhang, and L. Xie, "Coordination of wind farms and flywheels for energy balancing and frequency regulation," in *Proc. IEEE PES General Meeting*, Detroit, MI, Jul. 24-29, 2011, pp. 1–7.

[3] A. A. Thatte and L. Xie, "Towards a unified operational value index of energy storage in smart grid environment," *IEEE Trans. Smart Grid*, accepted.

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