IOWA STATE UNIVERSITY

EE 653 Power distribution system modeling, optimization and simulation

An Overview of Energy Storage Systems (ESS) for Electric Grid Applications

GRA: Jinqiang Liu

Advisor: Dr. Zhaoyu Wang

Department of Electrical and Computer Engineering

Iowa State University

Outline

- Classification of Energy Storage Technologies
  - Mechanical Energy Storage Systems
  - Electrochemical Energy Storage Systems
  - Chemical Energy Storage Systems
  - Electrical Energy Storage Systems
  - Thermal Energy Storage Systems
- Applications of Energy Storage Systems in Power Grid
  - Energy Arbitrage
  - Capacity Credit
  - Ancillary Services
  - Customer Side Benefits
- Optimization formulations for battery dispatch

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Mechanical Energy Storage Systems

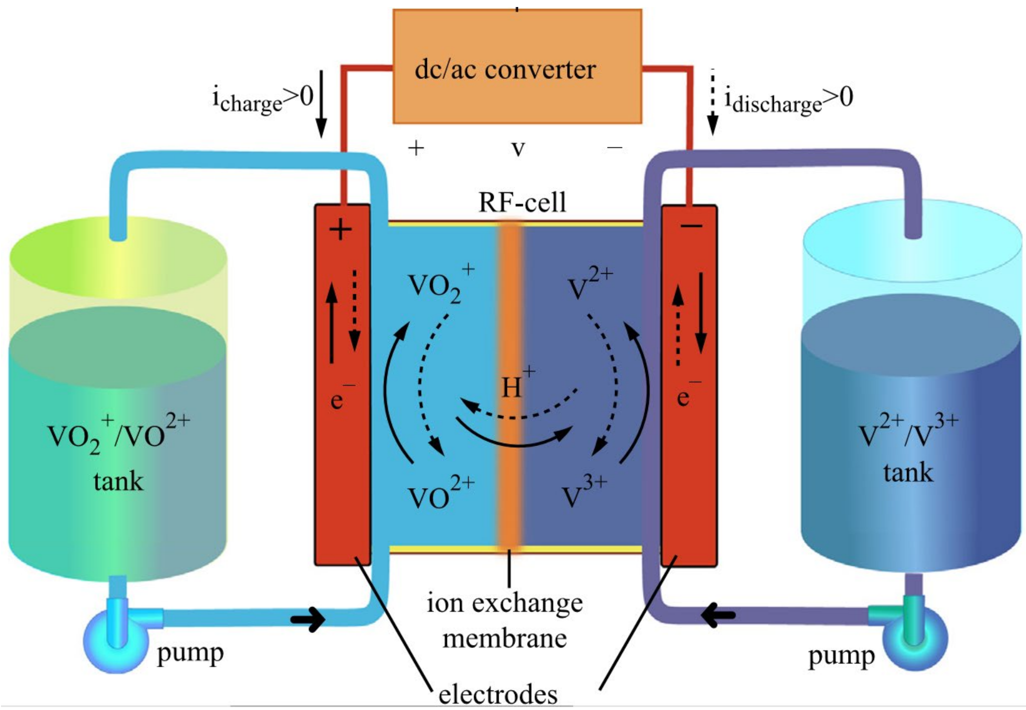
Mechanical ESS utilize different types of mechanical energy as the medium to store and release electricity according to the demand of power systems.

- Flywheel ESS store electricity in the form of rotational kinetic energy
  - High power density and fast response
  - Large initial investment and high rates of energy loss
- Pump hydro ESS store and release energy through two water reservoirs with a considerable vertical height difference
  - Good technological maturity and commercial availability
  - Adverse environmental impact and geological sitting limitation
- Compressed air ESS utilize the electricity to power compressors to store the energy in the form of compressed air in a vessel, while the energy can be released into a gas turbine to save the use of natural gas.
  - Commercial availability for very high power and energy with a single unit
  - Difficult to find a suitable geologic storage medium like a hard-rock cavern, salt cavern, or aquifer storage)

Electrochemical Energy Storage Systems

Energy is transferred between electrical and chemical energy stored in active chemical compounds through reversible chemical reactions.

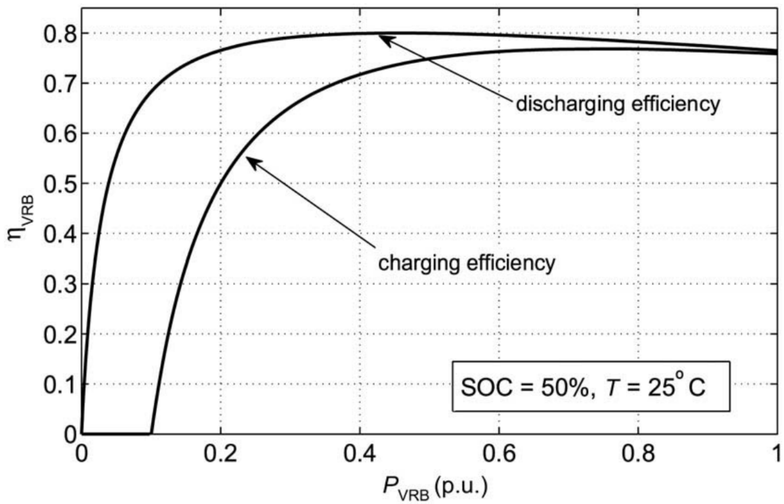
- Flow batteries convert electricity to chemical energy stored in an electrolyte flowing through a reactor and release the energy by the reverse reaction



Alotto, Piergiorgio, Massimo Guarnieri, and Federico Moro. "Redox flow batteries for the storage of renewable energy: A review." *Renewable and sustainable energy reviews* 29 (2014): 325-335.

Flow Battery ESS

- The vanadium redox flow battery is one of the most popular types of flow batteries
  - Large capacity of single unit, long cycle life
  - Environmental impact of toxic ion-exchange membrane, low energy density
- The charge and discharge efficiencies of vanadium redox flow battery varies greatly with the output power



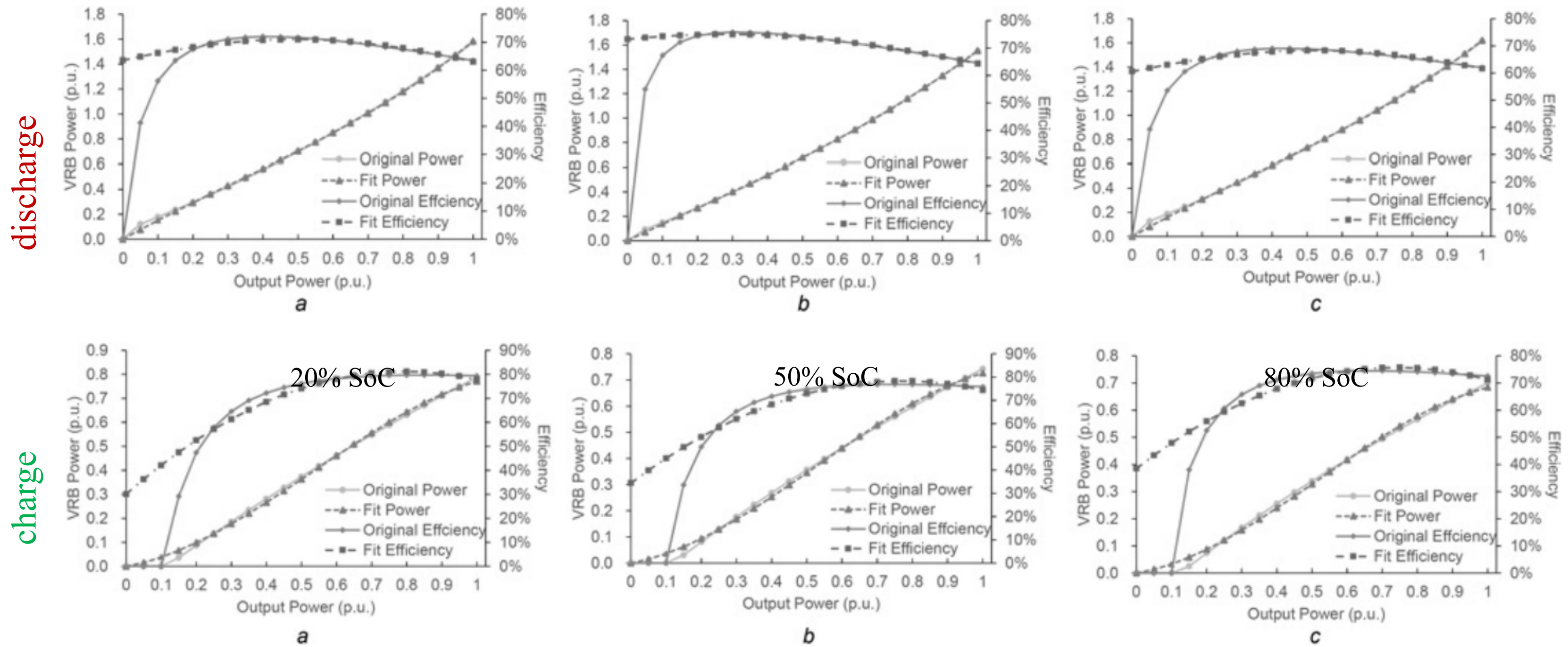
➢The efficiency initially increase along with the output power and then slightly decrease along with the output power.

➢An optimal operation point exist at either charge or discharge operation for the maximal efficiency.

Nguyen, Tu A., Mariesa L. Crow, and Andrew Curtis Elmore. "Optimal sizing of a vanadium redox battery system for microgrid systems." IEEE transactions on sustainable energy 6.3 (2015): 729-737.

Flow Battery ESS

- The charge and discharge efficiencies of vanadium redox flow battery are also dependent on the state of charge (SoC)

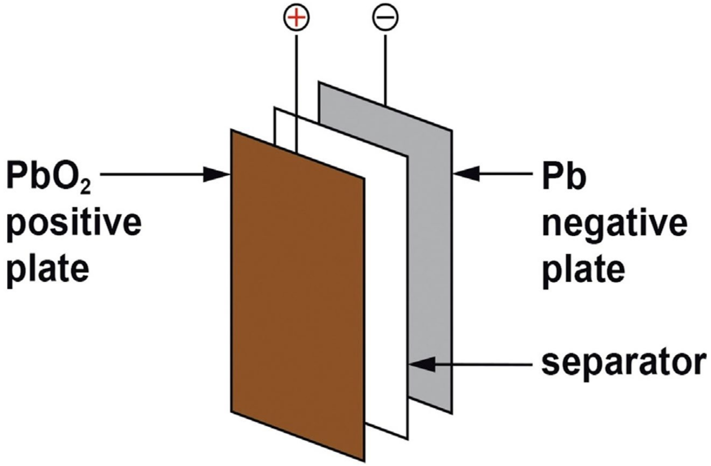


- ➢ The battery with 50% SoC possesses a better efficiency curve at the discharge mode
- ➢ The battery with 20% SoC possesses a better efficiency curve at the charge mode

He, Guannan, et al. "Optimal operating strategy and revenue estimates for the arbitrage of a vanadium redox flow battery considering dynamic efficiencies and capacity loss." IET Generation, Transmission & Distribution 10.5 (2016): 1278-1285.

Lead-acid Battery ESS

- The lead-acid battery has more than 100-year history like PHES and has been applied to some commercial ESS projects.



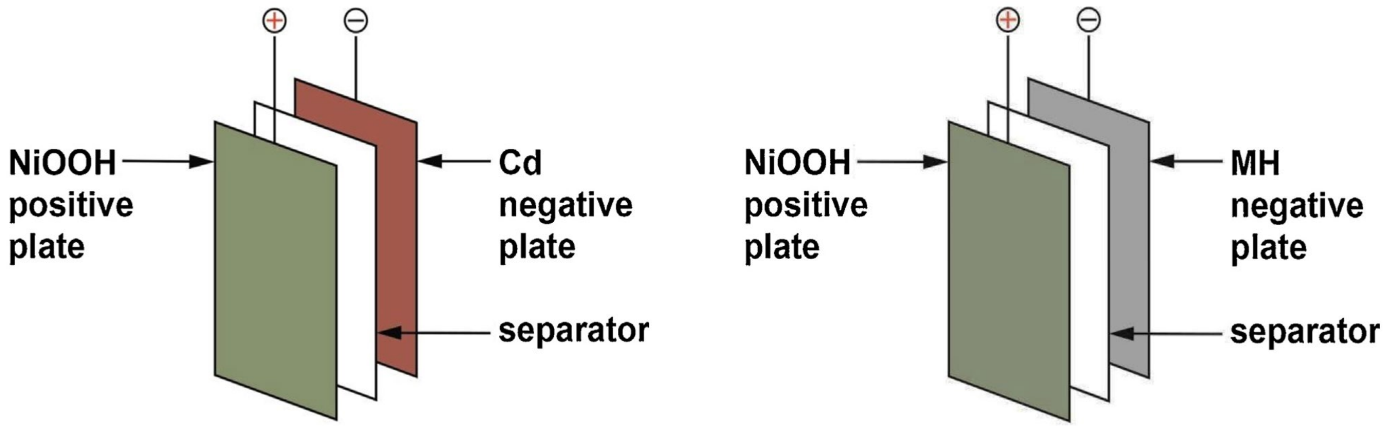
Power/Capacity	Location
10 MW/40 MWh	Chino, California
20 MW/14 MWh	Puerto Rico Electric Power Authority Metro

- Low cost and high reliability
- Low energy density, short cycle life, performance degradation in low temperatures

May, Geoffrey J., Alistair Davidson, and Boris Monahov. "Lead batteries for utility energy storage: A review." *Journal of Energy Storage* 15 (2018): 145-157.

Nickel-based Battery ESS

- A nickel hydroxide positive electrode and other active materials as negative electrodes, such as Fe, Cd, Zn, H2, and metal hydrides (MH)



Power/Duration	Location
27 MW/15 mins	Golden Valley Electric Association
3 MW/2 mins	Island of Bonaire (in company with wind energy)

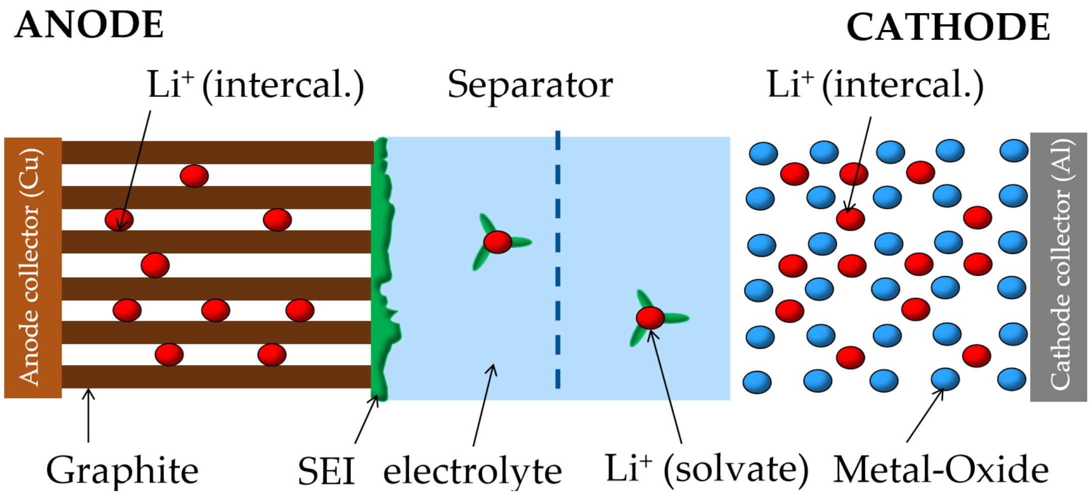
Higher energy density and longer cycle life than the lead-acid battery

Memory effect, high self-discharge, and reduction of power and capacity from overcharge

May, Geoffrey J., Alistair Davidson, and Boris Monahov. "Lead batteries for utility energy storage: A review." *Journal of Energy Storage* 15 (2018): 145-157.

Lithium-ion Battery ESS

- Li-ions travel from the cathode to anode through an electrolyte solution while the current flows from the anode to cathode in an external circuit

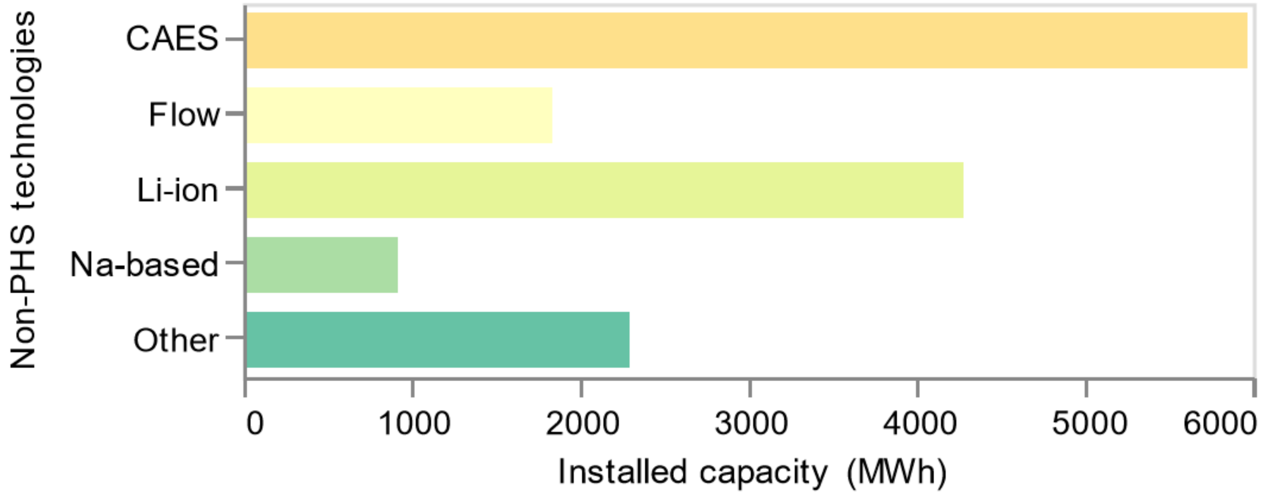


Parameter	NMC: C	NCA:C	LFP:C	LFP:LTO
Cost per kWh	++	+	–	– –
Cycle life	–	–	+	+
Status	Market	Market	Market	Research

Hesse, Holger C., et al. "Lithium-ion battery storage for the grid—a review of stationary battery storage system design tailored for applications in modern power grids." *Energies* 10.12 (2017): 2107.

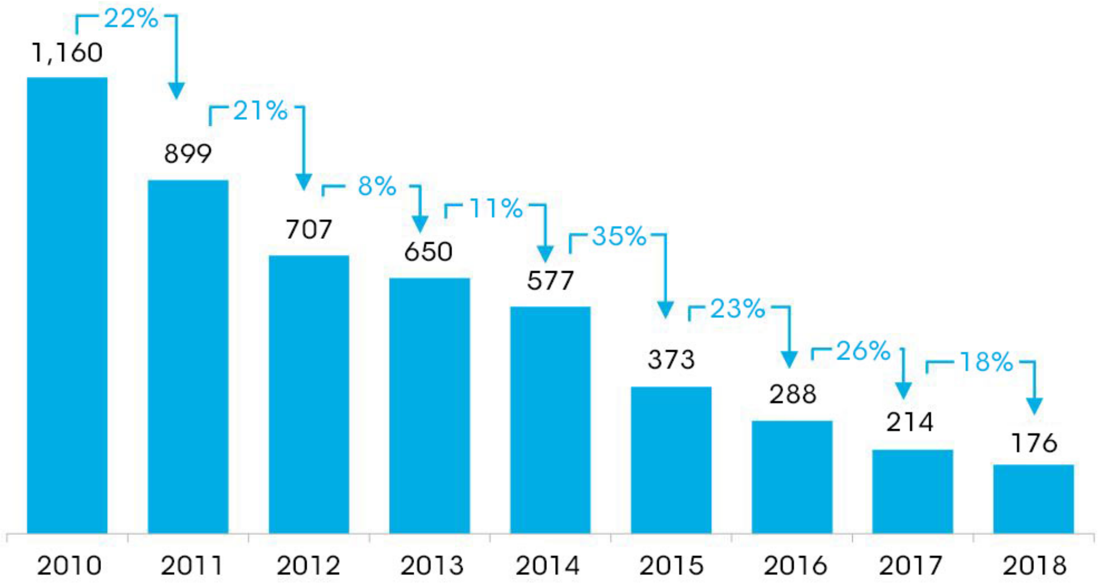
Lithium-ion Battery ESS

- Li-ions batteries ESS are increasingly deployed in electric grids



Lithium-ion Battery ESS

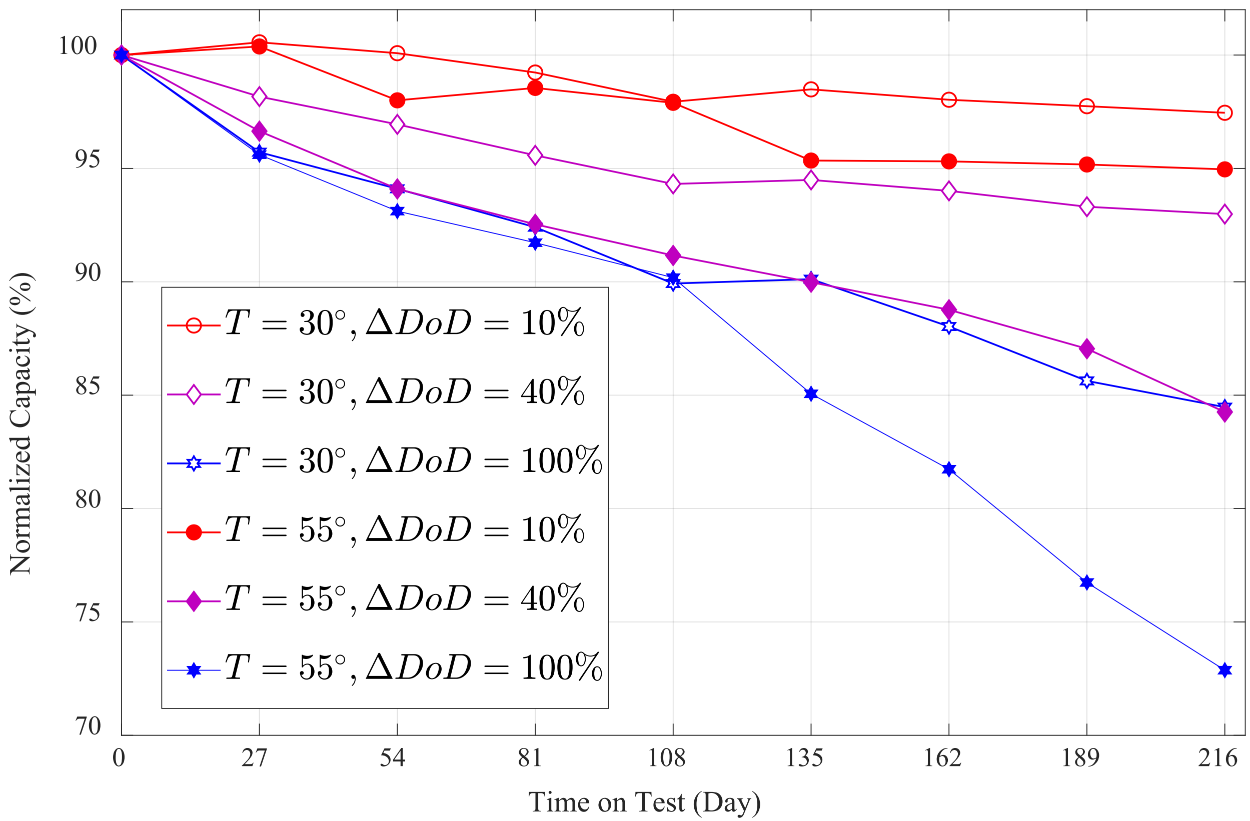
- Li-ions batteries are an ideal choice for ESS
  - Highest energy density among all electrochemical ESS and long cycle life
  - High cost and fast aging resulting from deep charge and discharge cycling
- The costs of Li-ion batteries are expected to continuously decrease



Source: BloombergNEF

Lithium-ion Battery ESS

Panasonic 18650 cells aging test



- Higher depth of cycle ΔDoD accelerates the battery capacity degradation
- Higher temperature T also accelerates the battery capacity degradation

Sodium-ion Battery ESS

- Sodium-beta batteries use sodium (Na) as the anode material. They are distinguished from other batteries due to their solid electrolyte beta-alumina.

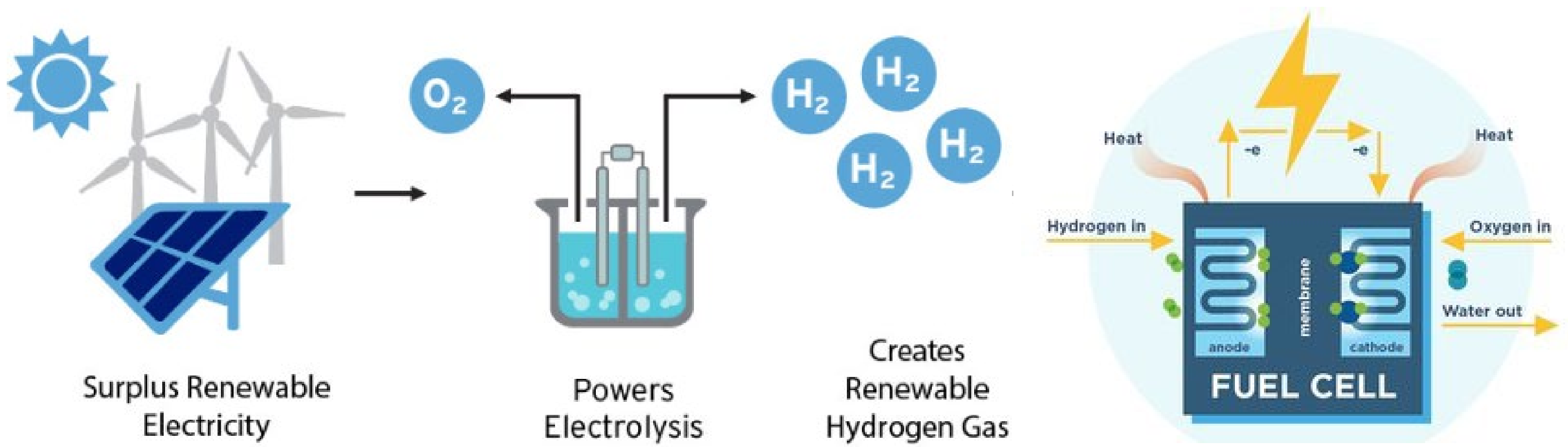
  - High power and energy density and long cycle life
  - High operation temperature at about 350 °C, high internal resistance, and Na erosion

1 MW NAS Battery System installed in Luverne, MN

4 MW NAS Battery installation at Presidio, TX

Chemical Energy Storage Systems

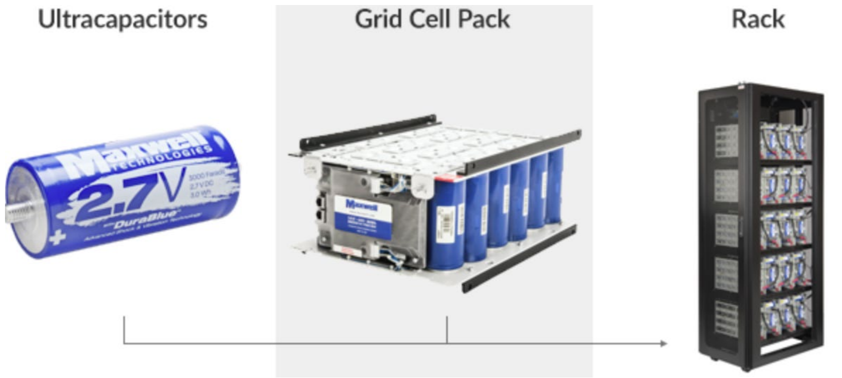
- Chemical energy storage systems (CESS) generate electricity through some chemical reactions releasing energy.
- Unlike electrochemical storage technology, the fuel and oxidant are externally supplied and need to be refilled for recycling in a fuel cell.
- CESS have largely been developed using hydrogen due to its excellent characteristics as fuel and its very high energy density
- However, the high cost and low efficiency place critical limitations for the broad applications of hydrogen fuel cells.



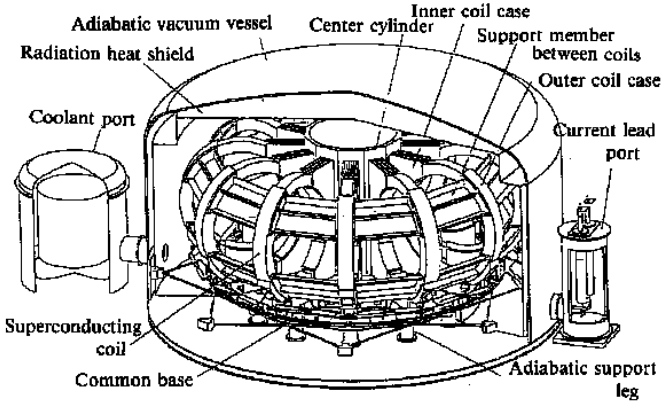
http://www.fchea.org/in-transition/2019/7/22/unlocking-the-potential-of-hydrogen-energy-storage

Electrical Energy Storage Systems

- Ultra-capacitors (UC) have high power density, 95% efficiency, and long lifetime, but suffer from high self-discharge rate and high cost.
- Many researchers are currently developing nanostructured materials to improve the performance of UC.
- Superconducting magnetic energy storage systems(SMESS) store electricity in the magnetic field through a large current circulating in a superconducting coil.
- Current studies focus on reducing the cost of coils and temperature control system.



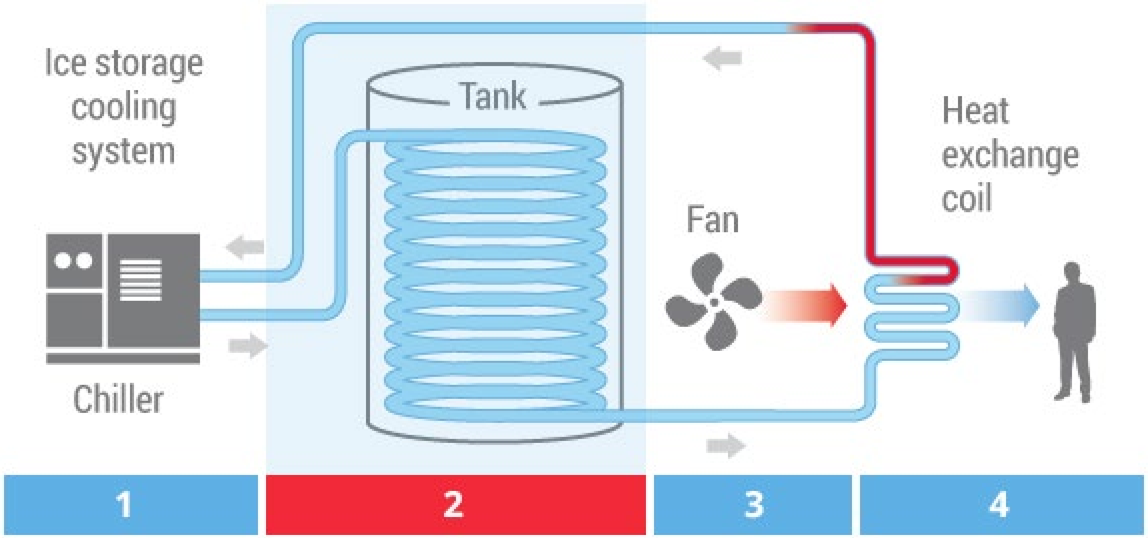
https://www.maxwell.com/products/ultracapacitors/grid-cell-pack



http://www.wtec.org/loyola/scpa/02_06.htm

Thermal Energy Storage Systems

- Thermal energy storage systems (TESS) store energy in the form of heat for later use in electricity generation or other heating purposes.
- Depending on the operating temperature, TESS can be categorized into two groups: low-temperature (<200 °C) TESS and high-temperature TESS.
- High-temperature TESS can be further categorized into three sub-groups: latent heat, sensible heat, and thermal-chemical sorption storage systems.



http://www.calmac.com/how-energy-storage-works

Comparison of Energy Storage Technologies

Technology	Specific energy (Wh/kg)	Vol. energy density (Wh/L)	Efficiency (%)	Self discharge (% per day)	Response time	Lifetime (cycle)	Lifetime (year)	Unit energy cost (USD/kWh)
PHES [1], [31]	0.5-1.5	0-2	70-80	0-0.02	min	12-100k	30-100	5-100
CAES [36], [37]	30-214	2-6	54-70	0-1	min	10-100k	20-40	2-84
Flywheel [32], [38]	5-100	20-200	90-95	20-100	ms	100k-1m	15-25	1,500-6,000
Flow battery [6], [26], [39]	25-85	15-70	70	0-33.6	ms	0.3-14k	5-20	315-1,050
Lead-acid [40]	30-40	80-90	80-82	0.09-0.4	ms	0.25-2.5k	3-15	105-473
Ni-Cd [6], [29]	50-75	60-150	72	0.2-0.6	ms	2000-2500	10-20	800-1,500
Li-ion [28]	100-265 [41]	177-676	92-95	0.09-0.36	ms	0.5-20k	5-20	200-1260
Na-S	150-240 [42]	140-300	80	0.05-1	ms	1-10k	10-25	263-735
HFC [29]	0.8-100k	0.5-3k	∼20-50	-	s	1000+	5-15	1,500-3,00/kW
UC [29], [43]	1-20	10-30	85-98	40	ms	>50,000	10-30	6,000
SMES [32], [42]	0.5–5	0.2–2.5	95-98	10-15	ms	100k+	30	10,000
Thermal [25], [32]	-	1000 MJ/L	50	-0.05-1.0	h	-	20-30	3-60

- Li-ion and flow batteries are currently the most popular electrochemical choices of ESS.
- PHES still play a dominant role ($\approx 97.45\%$) in the existing ESS projects.
- Na-S and HFC have the potential to be increasingly deployed.
- High power density ESS with high energy density ESS.

Formulations of Energy Storage Technologies in Power Grids

Technology	Power limit	Ramp limit	Energy limit	Efficiency	Lifetime
Pump	✓	✓	✓	✓	fixed
Flow battery	✓	✗	✓	function of power and energy	function of operations
Li-ion	✓	✗	✓	✓	function of operations
Thermal	✓	✓	✓	✓	fixed

- Traditional pump hydro and thermal storage technologies take relatively longer time to increase or decrease, which necessitate the ramp limits.
- Flow battery's formulation will introduce dynamic efficiency constraints.
- For electrochemical battery, especially Li-ion, lifetime is dependent on the operation.

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Classification of ESS Applications

Based on the **physical locations** in the grid, ESS can be categorized into two groups: **in front of the meter** and **behind the meter**.

- ESS in front of the meter can be further divided into transmission and distribution subgroups.
- ESS behind the meter can be further divided into non-residential and residential subgroups.

ESS **service scopes** can be categorized into four groups: **wholesale market**, **transmission**, **distribution**, and **customer**.

- ESS located at the lower hierarchical levels of the grid could potentially provide services for the higher hierarchical levels of the grid.
- Some services at these higher levels may be unavailable due to specific performance requirements or direct control by the utility.

Classification of ESS Applications

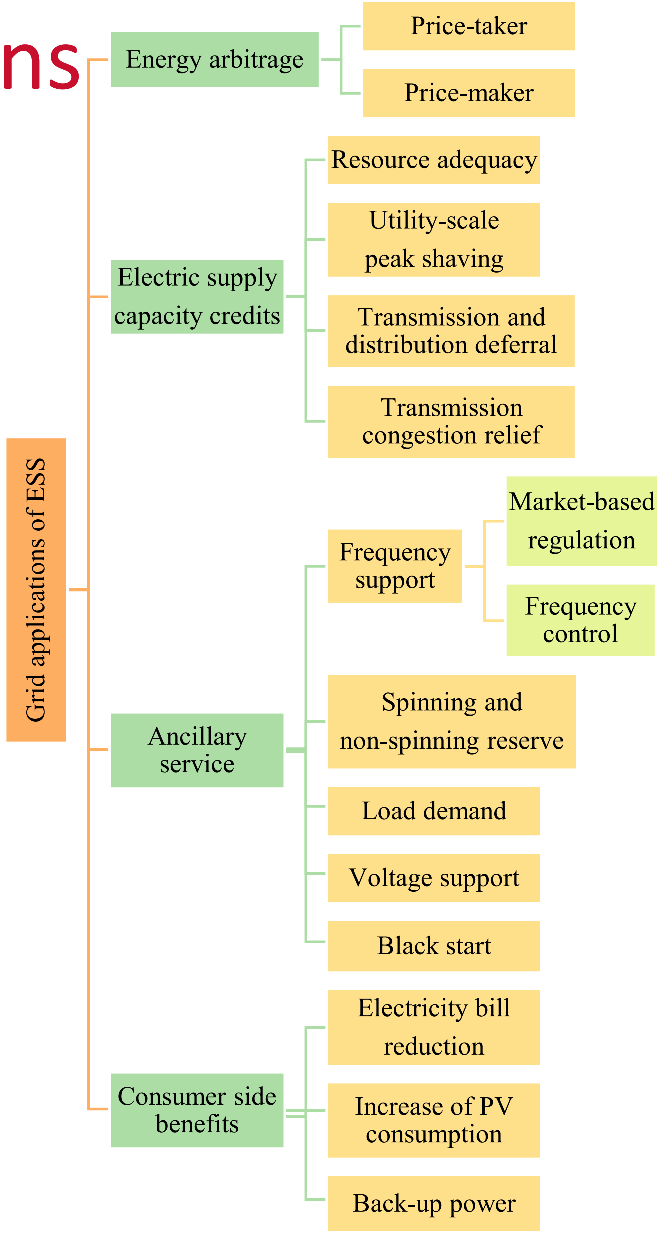
- Various grid applications of ESS that contribute to the increasing integration and consumption of renewable energy.
- For example, the voltage support and frequency regulation could alleviate the negative impact resulting from volatile power generated by the renewable energy sources.

			Grid domain		
			Transmission	**Distribution**	**Consumer**
Power rating (MW)			10s ~100s	0.010~10	0.002~2
Service scope	**Wholesale**	Energy arbitrage			
		Frequency regulation			
		Reserve			
		Resource adequacy			
		Demand response			
	Transmission	Transmission deferral			
		Voltage support			
		Inertia			
		Frequency response			
		Black start			
	Distribution	Distribution deferral			
		Voltage support			
		Reliability service			
		Microgrid			
	Consumer	Bill reduction			
		Increase PV consumption			
		Backup power			

Classification of ESS Applications

ESS applications are also distinguished with each other from their **working principles for gaining benefits**.

- **Energy-market** based applications focus on the utilization of ESS stored and released energy.
- **Capacity-related** applications include resource adequacy, utility-scale peak shaving, infrastructure deferral, and transmission congestion relief.
- **Ancillary services** mostly make use of the fast, directional, active and reactive power regulation of ESS.
- **Customer side benefits** consist of economic and environmental-friendly components.



Energy Arbitrage

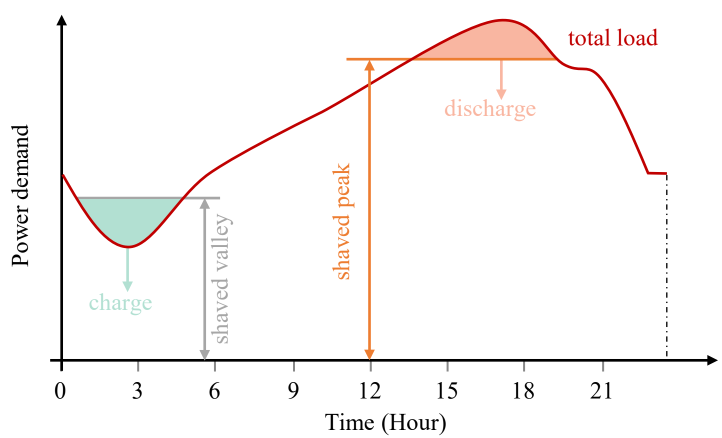
Energy arbitrage using ESS generally involves the purchase of cheap energy from the wholesale energy market for charging the ESS.

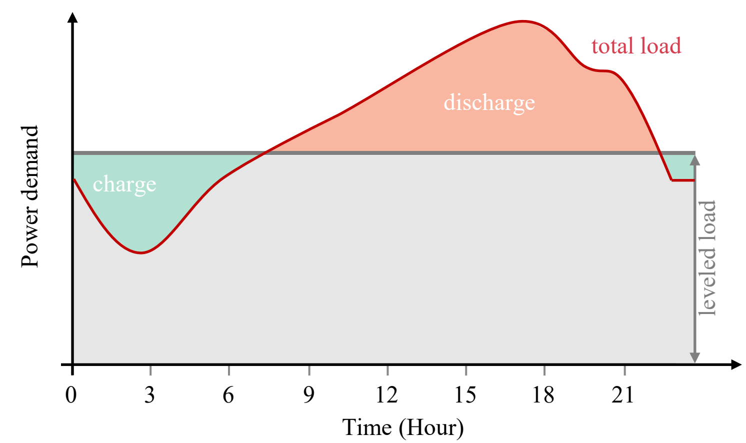
- Energy arbitrage is readily available for ESS interconnected to the transmission and distribution domain.
- Energy arbitrage can be realized by using many storage technologies without technical difficulties.
- The arbitrage algorithms can be divided into two groups by assuming ESS to be either a price taker or a price maker.
- It is difficult for battery storage systems to achieve cost-effective goal by solely implementing the energy arbitrage under the current battery storage costs and energy market conditions.

Electric Supply Capacity Credit

Capacity credit describes the ability of ESS to defer or reduce the need for upgrading existing generation, transmission, and distribution components that are used to supply peak demand and maintain system reliability

- To satisfy the increasing need for peaking capacity, the simple cycle combustion turbine is usually a default choice in the U.S. However, ESS are more efficient for shaving peak load due to its fast response, high energy efficiency, and inherent bidirectional power flow.





Resource adequacy

ESS can also earn profits from the wholesale capacity market by providing resource adequacy.

- Some capacity markets define the qualifying capacity of the ESS to be the maximum power rate at which the ESS can continuously discharge for four hours.
- Resource adequacy is extremely important for maintaining power system reliability. Therefore, ESS offering resource adequacy capacity is subject to a must-offer obligation in the California Independent System Operator (CAISO).
- Large ESS installed in front of the meter currently participate in the CAISO capacity market in the form of a non-generator resource (NGR) model that allows it to extract energy from the grid.
- For ESS behind the meter, it can provide resource adequacy in the form of a demand response participation model.

Transmission and distribution deferral

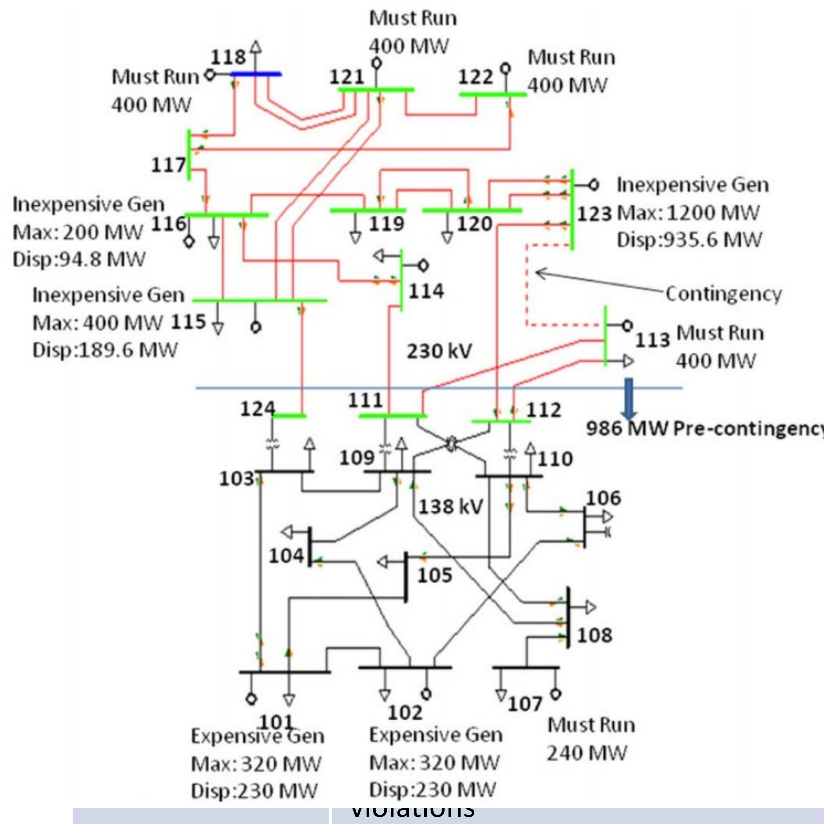
By effectively reducing peak loading, ESS defer investment for additional transmission and distribution capacity and extend the useful life of existing infrastructures.

- A probability method is proposed to quantify the benefits of the combination of ESS and real time thermal rating(RTTR) on deferring or preventing network reinforcement [1].
- The optimal deployment of ESS is presented in [2] for the deferral of distribution feeder upgrade. Several important factors that influence the deferral cost savings are studied, such as the cost of battery and feeder upgrade, and the annual rate of load increase.

[1] Greenwood, David M., et al. "A probabilistic method combining electrical energy storage and real-time thermal ratings to defer network reinforcement." IEEE Transactions on Sustainable Energy 8.1 (2016): 374-384.
[2] T. Zhang, A. E. Emanuel, and J. A. Orr, “Distribution feeder upgrade deferral through use of energy storage systems,” in Power and Energy Society General Meeting (PESGM), 2016. IEEE, 2016, pp. 1–5.

Transmission congestion relief

- A survey of different ESS applications on transmission systems is presented in [1]
- The continuation method is used to gradually increase the amount of transfer power to the thermal limits of transmission paths, including the overload of a line, transformer or a substation component.
- A sensitivity analysis and analytic hierarchical process model are combined to find the best locations of ESS to reduce the power flow of critical components.



[1] A. D. Del Rosso and S. W. Eckroad, “Energy storage for relief of transmission congestion,” IEEE Transactions on Smart Grid, vol. 5, no. 2, pp. 1138–1146, 2014.

Transmission congestion relief

- A MILP based real-time optimal dispatch algorithm is proposed in [1] to maximize its arbitrage profit while penalizing the power deviations from congestion relief commands. However, the financial benefits of ESS' contribution to transmission congestion relief have not been clearly quantified.
- Further, an adaptive penalty factor is used to achieve the highest possible contribution to congestion relief [2].
- ESS are proposed to be an alternative to transmission upgrades by absorbing excess wind energy during a congested period and releasing it when the power flow decreases [3].
- The dynamic interactions among wind curtailment, ramp rates of generating plants, and ESS are illustrated in [4].

[1] H. Khani and R. D. Zadeh, "Energy storage in an open electricity market with contribution to transmission congestion relief," in PES General Meeting— Conference & Exposition, 2014 IEEE. IEEE,2014, pp. 1–5.

[2] H. Khani, M. R. D. Zadeh, and A. H. Hajimiragha, "Transmission congestion relief using privately owned large-scale energy storage systems in a competitive electricity market," IEEE Transactions on Power Systems, vol. 31, no. 2, pp. 1449–1458, 2016.

[3] M. Korpaas, A. T. Holen, and R. Hildrum, "Operation and sizing of energy storage for wind power plants in a market system," International Journal of Electrical Power & Energy Systems, vol. 25, no. 8, pp. 599– 606, 2003.

[4] L. S. Vargas, G. Bustos-Turu, and F. Larra´ın, "Wind power curtailment and energy storage in transmission congestion management considering power plants ramp rates," IEEE Trans. Power Syst, vol. 30, no. 5, pp. 2498–2506, 2015.

Voltage Regulation

- BESS can be used to increase/decrease the output current to mitigate voltage drop/rise along with the fluctuation of load demand [1].
- On the other hand, local real power-frequency (*P-f*) and reactive power-voltage (*Q-V*) droop controllers can be embedded into BESS for frequency and voltage control, respectively [2].
- ESS is proposed to indirectly controls its charging/discharging power for voltage regulation based on the broadcast signal from the distribution network operators [3].
- To mitigate the voltage variations with the increasing penetration of solar energy, BESS and PV inverters are coordinated with upstream step voltage regulators for real-time voltage regulation [4].

[1] U. Datta, A. Kalam, and J. Shi, "Battery energy storage system to stabilize transient voltage and frequency and enhance power export capability," IEEE Transactions on Power Systems, 2018
[2] K. K. Mehmood, S. U. Khan, S.-J. Lee, Z. M. Haider, M. K. Rafique, and C.-H.Kim, "Optimal sizing and allocation of battery energy storage systems with wind and solar power dgs in a distribution network for voltage regulation considering the lifespan of batteries," IET Renewable Power Generation, vol. 11, no. 10, pp. 1305–1315, 2017.
[3] K. Christakou, D.-C. Tomozei, M. Bahramipanah, J.-Y. Le Boudec, and M.Paolone,"Primary voltage control in active distribution networks via broadcast signals: The case of distributed storage," IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2314–2325, 2014.
[4] L.Wang,F.Bai,R.Yan,andT.K.Saha,"Real-time coordinated voltage control of PV inverters and energy storage for weak networks with high PV penetration," IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 3383–3395, 2018

Voltage Regulation

- A model predictive control method is implemented to adjust reactive power generation from ESS and PV inverters in microgrids to minimize the total transmission loss and active power from the utility and maintain voltages of nodes at required range [1].
- The distributed optimal control has also been implemented for voltage regulation [2]. First, a local droop control method determines the total amount of charging/discharging power to alleviate voltage variations. Next, a weighted consensus control algorithm allocates the total power among multiple BESS according to the capacity. Finally, a dynamic consensus control algorithm ensures each BESS to approach the estimated system average SoC.

[1] V. Zamani, A. Cort´es, J. Kleissl, and S. Mart´ınez, "Integration of PV generation and storage on power distribution systems using MPC," in Power & Energy Society General Meeting, 2015 IEEE. IEEE, 2015, pp. 1–5.
[2] M. Zeraati, M. E. H. Golshan, and J. M. Guerrero, "Distributed control of battery energy storage systems for voltage regulation in distribution networks with high PV penetration," IEEE Transactions on Smart Grid, vol. 9, no. 4, pp. 3582–3593, 2018.

Frequency Regulation

- Local droop control enables ESS to inject power into the grid when grid frequency is lower than the trigger value for primary frequency regulation and to extract the excess power from the grid to mitigate its frequency increase [1].
- Li-ion BESS are utilized to mitigate frequency fluctuations due to high wind penetration through the rate of change of frequency (ROCOF) based inertial control [2].
- Mercier et al. propose an optimal sizing and operation method for a lead acid BESS providing primary frequency regulation, allowing the BESS to dynamically adjust its SoC limits [3].

[1] D. Kottick, M. Blau, and D. Edelstein, "Battery energy storage for frequency regulation in an island power system," IEEE Transactions on Energy Conversion, vol. 8, no. 3, pp. 455–459, 1993.
[2] V. Knap, R. Sinha, M. Swierczynski, D.-I. Stroe, and S. Chaudhary, "Grid inertial response with lithium-ion battery energy storage systems," in Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium on. IEEE, 2014, pp. 1817–1822.
[3] P.Mercier,R.Cherkaoui,andA.Oudalov,"Optimizingabatteryenergy storage system for frequency control application in an isolated power system,"IEEETransactionsonPowerSystems,vol.24,no.3,pp.1469– 1477, 2009.

Frequency Regulation

- For quantitative assessment of ESS effectiveness in the secondary frequency regulation, Zhang et al. propose a model to calculate the required capacity for frequency regulation [1].
- The results in their study show that ESS are more effective than conventional generators when the proportion of ESS among regulation resources is lower than 25%. However, the total required regulation capacity would increase when ESS share a larger proportion, which is caused by an increased probability of ESS saturation or depletion.
- The authors assume that the allocation of Automatic Generation Control (AGC) command is proportional to the capacity of ESS and conventional generators, which is unfavorable for ESS and replaced by more advanced allocation algorithm in some other research.

[1] F. Zhang, Z. Hu, X. Xie, J. Zhang, and Y. Song, "Assessment of the effectiveness of energy storage resources in the frequency regulation of a single-area power system," IEEE Transactions on Power Systems, vol. 32, no. 5, pp. 3373–3380, 2017.

Frequency Regulation

- Various transmission system operators generate a high frequency and energy-neutral AGC signal for ESS, such as the Independent System Operator-New England (ISO-NE) energy-neutral continuous (ENC) and PJM dynamic regulation (RegD) signals.
- An optimal secondary frequency control method directly allocates the AGC signal to different ESS and the problem is solved by a distributed optimization algorithm [1].
- Energy arbitrage and frequency regulation are co-optimized to obtain maximum profit by using a multi-scale dynamic programming method in [2].

[1] O. Megel, T. Liu, D. J. Hill, and G. Andersson, "Distributed secondary frequency control algorithm considering storage efficiency," IEEE Transactions on Smart Grid, 2017.
[2] B. Cheng and W. B. Powell, "Co-optimizing battery storage for the frequency regulation and energy arbitrage using multi-scale dynamic programming," IEEE Transactions on Smart Grid, vol. 9, no. 3, pp. 1997–2005, 2018

Spinning and Non-Spinning Reserves

- Spinning reserve represents the total reserved generation capacity of all synchronized generators, plus the available power capacity of the online ESS providing spinning reserve.
- Non-spinning reserve indicates the offered capacity of reserved off-line plants and ESS.
- An adaptive operation strategy is presented to allocate the output power of multiple ESS for offering spinning reserve [118].
- BESS can also support the operation of a microgrid as a source of spinning reserve, which helps the microgrid meet reserve requirements [2].
- In market-based research, ESS can participate in the spinning reserve market either as a price taker [3] or a price maker [4].

[1] W.-W. Kim, J.-S. Shin, and J.-O. Kim, "Operation strategy of multienergy storage system for ancillary service," IEEE Trans Power Syst PP (99), pp. 1–1, 2017.
[2] S. Chen, H. B. Gooi, and M. Wang, "Sizing of energy storage for microgrids," IEEE Transactions on Smart Grid, vol. 3, no. 1, pp. 142– 151, 2012.
[3] G. He, Q. Chen, C. Kang, and Q. Xia, "Optimal operating strategy and revenue estimates for the arbitrage of a vanadium redox flow battery considering dynamic efficiencies and capacity loss," IET Generation, Transmission & Distribution, vol. 10, no. 5, pp. 1278–1285, 2016
[4] E. Nasrolahpour, J. Kazempour, H. Zareipour, and W. D. Rosehart, "A bilevel model for participation of a storage system in energy and reserve markets," IEEE Transactions on Sustainable Energy, vol. 9, no. 2, pp. 582–598, 2018.

Customer Side Benefits

- For commercial and industrial customers, ESS can shave the peak load to reduce the demand charge paid for utilities. For customers eligible for time-of-use (TOU) electricity energy pricing, ESS can shift some load from on-peak period to off-peak period to save electricity costs.

Rate Schedule	Season	Demand Charge (per kWh)	Time-of-Use	Energy Charges (per kWh)
A-10 TOU Secondary	**Summer**	$20.46	Peak	$0.23427
			Part-Peak	$0.17914
			Off-Peak	$0.15107
	Winter	$11.94	Part-Peak	$0.14974
			Off-Peak	$0.13268
A-10 TOU Primary	**Summer**	$19.25	Peak	$0.22021
			Part-Peak	$0.16965
			Off-Peak	$0.14303
	Winter	$12.17	Part-Peak	$0.14592
			Off-Peak	$0.13004
A-10 TOU Transmission	**Summer**	$13.13	Peak	$0.18102
			Part-Peak	$0.13414
			Off-Peak	$0.10884
	Winter	$9.17	Part-Peak	$0.12235
			Off-Peak	$0.10778

From Pacific Gas and Electric Company (PG&E)

Customer Side Benefits

- Customers can also utilize ESS to improve their PV self-consumption by storing excess PV generation into the ESS and releasing it when PV generation cannot solely meet the load demand.
- The self-consumption factor is defined as the proportion of the load that is powered by the PV generator and battery system, where the battery system can exchange energy only with the PV generator [1].
- The PV self-consumption factor increases from 30.9% to 72.1% by employing a BESS with the capacity being approximately half of the daily load [1].
- BESS is controlled to reduce the mismatch between residential PV generation and load demand, which consequently reduces the energy sold to and purchased from the grid by 76% and 78.3% [2].

[1] M. Castillo-Cagigal, E. Caamano-Mart´ın, E. Matallanas, D. MasaBote, A. Guti´errez, F. Monasterio-Huelin, and J. Jim´enez-Leube, "PV self-consumption optimization with storage and Active DSM for the residential sector," Solar Energy, vol. 85, no. 9, pp. 2338–2348, 2011.
[125] F. M. Vieira, P. S. Moura, and A. T. de Almeida, "Energy storage system for self-consumption of photovoltaic energy in residential zero energy buildings," Renewable Energy, vol. 103, pp. 308–320, 2017

Outline

- Classification of Energy Storage Technologies
  - Mechanical Energy Storage Systems
  - Electrochemical Energy Storage Systems
  - Chemical Energy Storage Systems
  - Electrical Energy Storage Systems
  - Thermal Energy Storage Systems
- Applications of Energy Storage Systems in Power Grid
  - Energy Arbitrage
  - Capacity Credit
  - Ancillary Services
  - Customer Side Benefits
- Optimization formulations for battery dispatch

Optimal Bidding in the Joint Power Markets

- The daily profit is equal to the sum of revenues from each market minus the operational and maintenance costs

$$\max_{Cap_t^e, Cap_t^{reg}, Cap_t^{res}} \min\left(T_{cycle}, T_{float}\right) P^{day}$$

$$\begin{aligned}
P^{day} = & \sum_{\substack{s \in S,\\ t \in T}} \rho_s \left(c_{s,t}^{DA} Cap_t^e + c_{s,t}^{RT} \gamma_t^{res} Cap_t^{res}\right) \Delta T \\
& + \sum_{\substack{s \in S,\\ t \in T}} \rho_s c_{s,t}^{res} Cap_t^{res} \\
& + \sum_{\substack{s \in S,\\ t \in T}} \rho_s \mu^{perf} \left(c_{s,t}^{reg,cap} Cap_t^{reg} + c_{s,t}^{reg,perf} Cap_t^{reg} r^m\right) \\
& - c^O \sum_{t \in T} \Delta T \left[Cap_t^e + \gamma_t^{res} Cap_t^{res} + 2\gamma_t^{reg} Cap_t^{reg}\right] \\
& - c^M P_{max}
\end{aligned}$$

Optimal Bidding in the Joint Power Markets

The operational constrains of the battery storage

1) *Capacity constraints*

$$Cap_t^e - \sigma Cap_t^{reg} \geq -P_{max}$$
$$Cap_t^e + \sigma Cap_t^{reg} + Cap_t^{res} \leq P_{max}$$

2) *No ramp constraints for battery ESS*
3) *Energy constraints for providing ancillaryy services*

$$E_t \geq \left(Cap_t^e \Delta T + Cap_t^{res} \Delta T + Cap_t^{reg} \Delta T_{min}^{reg}\right) / \eta_d$$
$$E_t \leq E_{max} - \left(Cap_t^e \Delta T - Cap_t^{reg} \Delta T_{min}^{reg}\right) \eta_c$$

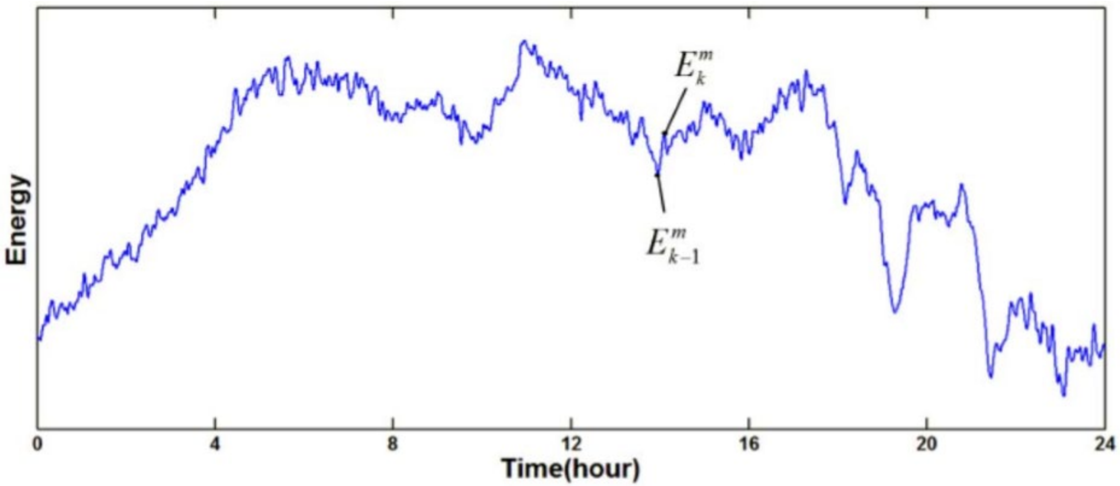
4) *State of charge constraints*

$$E_t = E_{t-1} + Cap_t^{e,buy} \Delta T \eta_c - Cap_t^{e,sell} \Delta T / \eta_d - \gamma_t^{res} Cap_t^{res} \Delta T / \eta_d$$
$$+\gamma_t^{res} Cap_t^{reg} \eta_c - \gamma_t^{res} Cap_t^{reg} / \eta_d$$

Optimal Bidding in the Joint Power Markets

Battery degradation is considered to calculate the life

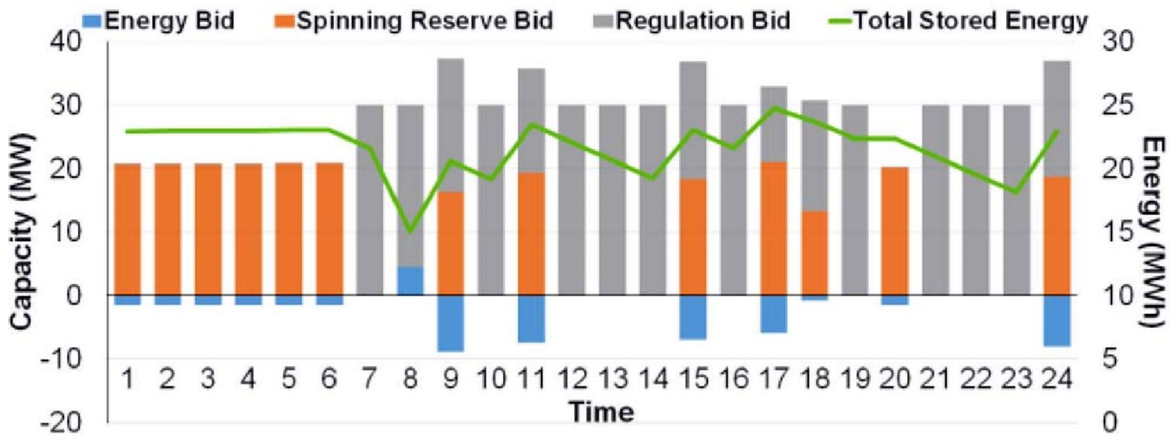
1) *Count the cycles based on the extreme points and separate the decision variables from the identification of half cycles.*



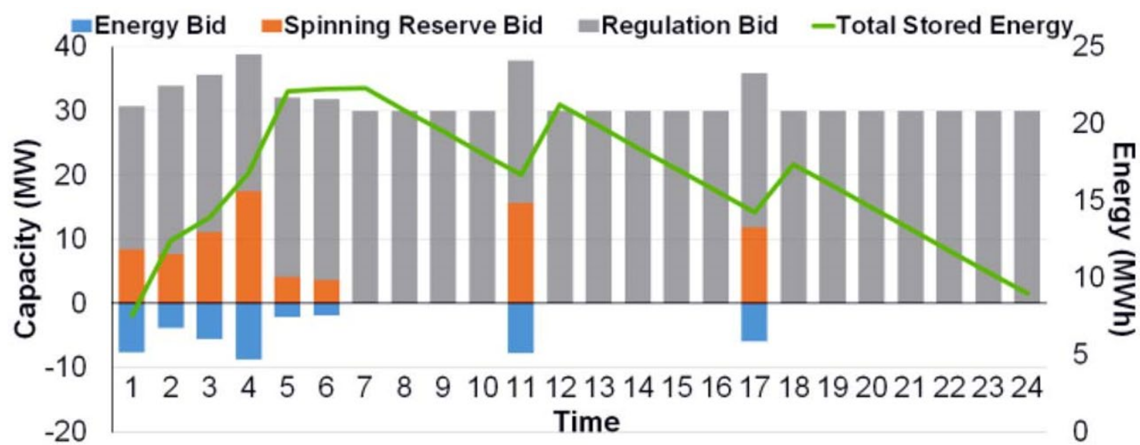
2) *Model the daily degradation as a power function of depth of cycles*

$$T_{cycle} = \frac{1}{\alpha \sum_{k \in K} d_{half,k}^{kp}}$$

Optimal Bidding in the Joint Power Markets



Optimal bidding strategies and energy curves of battery storage considering cycle life



Optimal bidding strategies and energy curves of battery storage without considering cycle life

Optimal Bidding in the Joint Power Markets

		Base case	No PBR payment	No cycle life
Daily Income ($)		19,462	15,591	23,790
Gross Income (mil. $)		114	91	88
Profit Rate		26.3%	1.2%	-2.2%
Daily Equivalent 100%-DOD Cycle Number	Decomposition Method	3.42	3.42	5.41
	Original Method	3.58	3.55	5.55
	Deviation Ratio	4.47%	3.52%	2.55%
Cycle Life (year)		10.0	10.0	6.3

- More advanced probabilistic modeling of volatile price profiles for achieving more effective results.
- More accurate modelling method of capacity degradation for incorporating long-term profit into the optimization.
- Improved methodology to solve the nonlinear optimization problem considering long-term profit.

[1] He, Guannan, et al. "Optimal bidding strategy of battery storage in power markets considering performance-based regulation and battery cycle life." *IEEE Transactions on Smart Grid* 7.5 (2015): 2359-2367.

Optimal battery participation in frequency regulation market

If the market clearing price and the regulation signal realization are known, the optimal regulation capacity and dispatch can be obtained by solving

$$\max_{Cap^{reg},\boldsymbol{p}} P^{day}(Cap^{reg},\boldsymbol{p}) \coloneqq \left(1-\frac{\|Cap^{reg}\boldsymbol{r}-\boldsymbol{p}\|_1}{Cap^{reg}\|\boldsymbol{r}\|_1}\delta\right)c^{reg}Cap^{reg}-A(\boldsymbol{p})$$

s.t.

$$1-\frac{\|Cap^{reg}\boldsymbol{r}-\boldsymbol{p}\|_1}{Cap^{reg}\|\boldsymbol{r}\|_1}\delta \geq \mu_{min}^{perf}$$

$$0 \leq Cap^{reg} \leq C_0$$

$$-C_0 \leq p_t \leq C_0$$

$$E_t = E_{t-1} + M\eta_c \max\{p_t, 0\} - M\min\{p_t, 0\}/\eta_d$$

$$\underline{E} \leq E_t \leq \bar{E}$$

Optimal battery participation in frequency regulation market

- However, this problem cannot be solved in real world because the realization is not known in advance.
- Therefore, a decision policy need to be determined.
- The expected profit corresponding to an operational policy and regulation capacity

$$J(g, Cap^{reg}) = E[P^{day}(Cap^{reg}, \boldsymbol{p})]$$
$$= E\left[\left(1 - \frac{\|Cap^{reg}\boldsymbol{r} - \boldsymbol{p}\|_1}{Cap^{reg}\|\boldsymbol{r}\|_1}\delta\right) c^{reg} Cap^{reg} - A(\boldsymbol{p})\right]$$

- By transform the performance requirement into a chance constraint, the initial problem is reformulated as

$$\max_{Cap^{reg}, g} E[c^{reg}]Cap^{reg} - \frac{\delta E[c^{reg}]}{E[\|\boldsymbol{r}\|_1]} E[\|C\boldsymbol{r} - \boldsymbol{p}^g\|_1 + A(\boldsymbol{p}^g)]$$

s.t.

$$\text{Prob}\left[1 - \frac{\|Cap^{reg}\boldsymbol{r} - \boldsymbol{p}\|_1}{Cap^{reg}\|\boldsymbol{r}\|_1}\delta \geq \mu_{min}^{perf}\right] \geq \xi;\ g \in G; Cap^{reg} \in [0, C_0]$$

Optimal battery participation in frequency regulation market

- The online regulation response policy takes a threshold form to balance the cost of deviating from the regulation signal and the cycle aging cost of batteries while satisfying operating constraints.
- The optimal regulation capacity is determined as the minimum between the rated power of the battery and the critical value that exactly guarantee the regulation response satisfy the minimum performance index with a predefined confidence.

CASE STUDY RESULTS IN PJM REGD MARKET 03/2016-02/2017

	Benchmark	Optimal participation under ξ performance confidence					
		$\xi = 99\%$	$\xi = 95\%$	$\xi = 90\%$	$\xi = 85\%$	$\xi = 75\%$	$\xi = 50\%$
Market income [k$]	1472.9	494.8	823.2	958.8	1035.9	1164.9	1266.8
Aging cost [k$]	1091.8	67.5	165.8	213.0	240.3	286	326.3
Prorated operating profit [k$]	381.1	427.3	657.4	745.7	795.6	878.6	940.5
Battery cell life expectancy [month]	9	69	42	35	33	29	26
Annual average performance	0.99	0.99	0.96	0.95	0.93	0.90	0.84
Hours of under-performance	6	81	204	246	297	426	1022
Total regulation capacity cleared [MW·h]	87600	14991	29051	36838	42166	54087	73504

[1] Xu, Bolun, et al. "Optimal battery participation in frequency regulation markets." *IEEE Transactions on Power Systems* 33.6 (2018): 6715-6725.

Optimal Battery Dispatch for Transmission Congestion Relief

- A more sophisticated multi-level optimization model is proposed to coordinate the transmission congestion with distributive objectives [1].
- This model determines the corrective schedule adjustments of ESS and conventional generating units by minimizing their deviations from the initially calculated economic schedules.

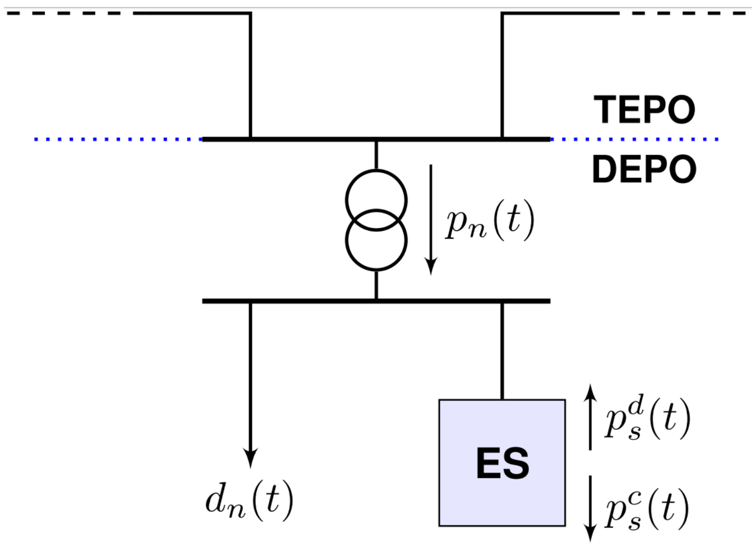


TABLE I
DESCRIPTION OF THE REPORTS

Name	Contents
Capacity	ESS power and energy capacity
Congestion forecast	Load forecast and TEPO charging indicator
Initial schedule	Initial DEPO injection schedule
Mitigation needs	Minimum and maximum net load
Final schedule	Final ESS combined injection schedule

[1] R. T. Elliott, R. Fernandez-Blanco, K. Kozdras, J. Kaplan, B. Lockyear, J. Zyskowski, and D. S. Kirschen, “Sharing energy storage between transmission and distribution,” IEEE Transactions on Power Systems, 2018.

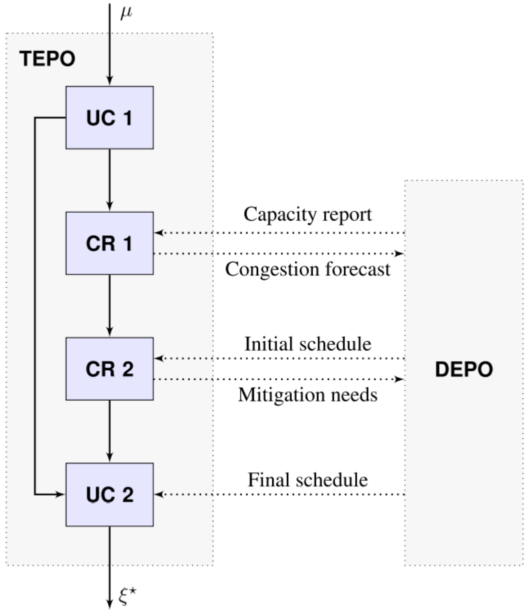
Optimal Battery Dispatch for Transmission Congestion Relief

- Stage 1(UC 1), Pre-mitigation unit commitment

In this stage, TEPO solves a standard unit commitment and economic dispatch without considering ESS or system security constraints.

$$\xi: (v_i, y_i, z_i, p_{ib}, p_i, x_k, x_w, \theta_n)$$

Variables	Description
v_i	Commitment of the *i*th CG
y_i	Startup status
z_i	Shutdown status
p_{ib}	Power of the *b*th generator cost curve segment
p_i	Total power output
x_k	Power curtailment of the *k*th solar plant
x_w	Power curtailment of the *w*th wind farm
θ_n	Voltage angle at bus *n*



[1] R. T. Elliott, R. Fernandez-Blanco, K. Kozdras, J. Kaplan, B. Lockyear, J. Zyskowski, and D. S. Kirschen, "Sharing energy storage between transmission and distribution," IEEE Transactions on Power Systems, 2018.

Optimal Battery Dispatch for Transmission Congestion Relief

- A standard minimum operating cost objective consisting of three components

$$f(\xi) = \sum_{t\in T}\sum_{i\in I} C_i(t) + \sum_{t\in T}\sum_{w\in W} C_w(t) + \sum_{t\in T}\sum_{k\in K} C_k(t)$$

- The conventional generating costs are given by

$$C_i(t) = c_i^{nl} v_i(t) + c_i^{su} y_i(t) + \sum_{b\in B} m_{ib} p_{ib}(t)$$

- Non-load cost + startup cost + *b*th segment of unit *i*'s cost curve

- Binary variable generation constraints

$$y_i(t) - z_i(t) = v_i(t) - v_i(t-1)$$
$$y_i(t) + z_i(t) \le 1$$

- Power output of each block and the total output is bounded such that

$$\bar{p}_i v_i(t) \le p_i(t) \le \bar{p}_i v_i(t)$$
$$0 \le p_{ib}(t) \le \bar{p}_{ib} v_i(t)$$

[1] R. T. Elliott, R. Fernandez-Blanco, K. Kozdras, J. Kaplan, B. Lockyear, J. Zyskowski, and D. S. Kirschen, "Sharing energy storage between transmission and distribution," IEEE Transactions on Power Systems, 2018.

Optimal Battery Dispatch for Transmission Congestion Relief

- Ramp constraints
- $\underline{R}_i \leq p_i(t) - p_i(t-1) \leq \bar{R}_i$
- Power transfer throughout the transmission network is modeled using a standard dc power flow approximation

$$F_i(t) = \left[\theta_{o(l)}(t) - \theta_{d(l)}(t)\right]/x_l$$

- The nodal power balance constraints can be stated as

$$d_n(t) = \sum_{i \in I_n} p_i(t) + \sum_{j \in J_n} p_j(t) + \sum_{k \in K_n} \hat{p}_k(t)$$

$$+ \sum_{k \in W_n} \hat{p}_w(t) - \sum_{l \in O_n} F_l(t) + \sum_{l \in D_n} F_l(t)$$

[1] R. T. Elliott, R. Fernandez-Blanco, K. Kozdras, J. Kaplan, B. Lockyear, J. Zyskowski, and D. S. Kirschen, “Sharing energy storage between transmission and distribution,” IEEE Transactions on Power Systems, 2018.

Optimal Battery Dispatch for Transmission Congestion Relief

- Stage 2(CR 1), independent congestion relief
- In this stage, TEPO solve an optimization with the capacity report to determine a minimal set of corrective actions required to alleviate congestion.

➢ Cardinality minimization is a NP-hard in general, but it is equivalent to l_p-norm minimization, l_1-norm is used as a convex approximation to the carnality function.

$$f(\xi) = \sum_{r \in R} |\alpha_r \xi_r| = \|A\xi\|_1$$

[1] R. T. Elliott, R. Fernandez-Blanco, K. Kozdras, J. Kaplan, B. Lockyear, J. Zyskowski, and D. S. Kirschen, "Sharing energy storage between transmission and distribution," IEEE Transactions on Power Systems, 2018.

Optimal Battery Dispatch for Transmission Congestion Relief

- In addition to the constraints in stage 1, the transmission power and energy storage constraints are introduced

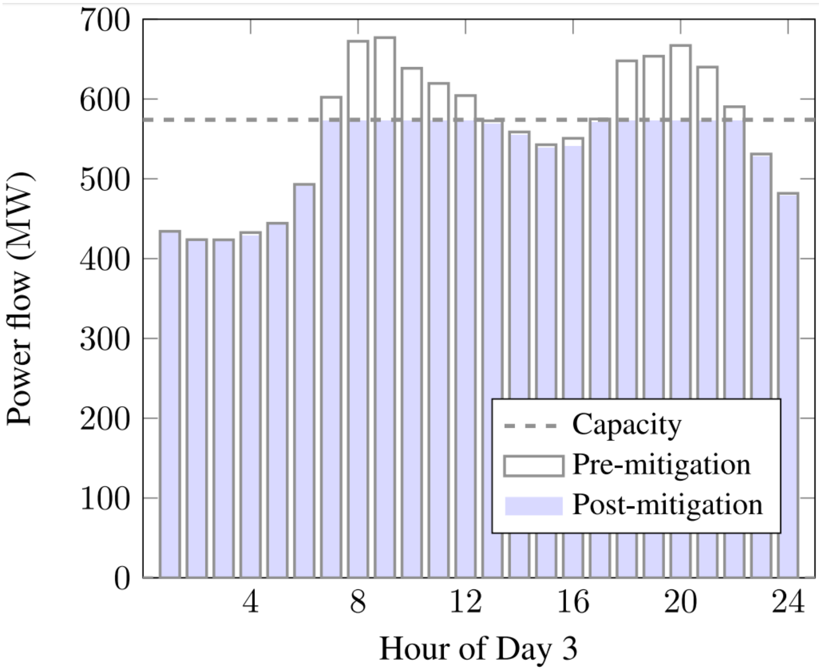
$$\underline{F_l} \leq F_l(t) \leq \bar{F}_l$$
$$0 \leq p_s^c(t) \leq \overline{p}_s^c v_s(t)$$
$$0 \leq p_s^d(t) \leq \overline{p}_s^d\left(1 - v_s(t)\right)$$
$$\overline{E}_s \leq E_s(t) \leq \underline{E_s}(t)$$
$$E_s\left(t_f\right) = E_s'$$

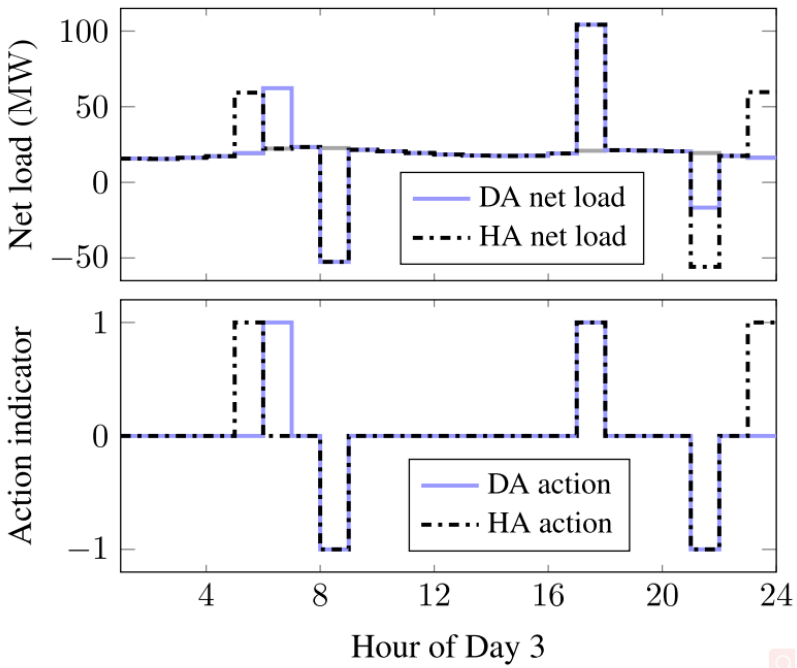
- In Stage 3(CR 2), TEPO solves an optimization with the consideration of DEPO's proposed ESS schedule. The formulation is nearly the same as in stage 2, except changing the ESS output power penalty function.
- TEPO sends DEPO the mitigation needs report. Based on this information, DEPO computes and returns the final ESS schedule.

[1] R. T. Elliott, R. Fernandez-Blanco, K. Kozdras, J. Kaplan, B. Lockyear, J. Zyskowski, and D. S. Kirschen, "Sharing energy storage between transmission and distribution," IEEE Transactions on Power Systems, 2018.

Optimal Battery Dispatch for Transmission Congestion Relief

- Stage 4, Post-Mitigation Unit Commitment
- This problem treats the ESS injection schedules determined in Stage 3 as inputs and solves for the least-cost generation schedule considering ESS injections and transmission capacity constraints.





[1] R. T. Elliott, R. Fernandez-Blanco, K. Kozdras, J. Kaplan, B. Lockyear, J. Zyskowski, and D. S. Kirschen, “Sharing energy storage between transmission and distribution,” IEEE Transactions on Power Systems, 2018.

Thank you!