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Optimal Distribution System Planning Considering Regulation Services and Degradation of Energy Storage Systems

Tsinghua-Berkeley Shenzhen Institute (TBSI)

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Content

Motivations

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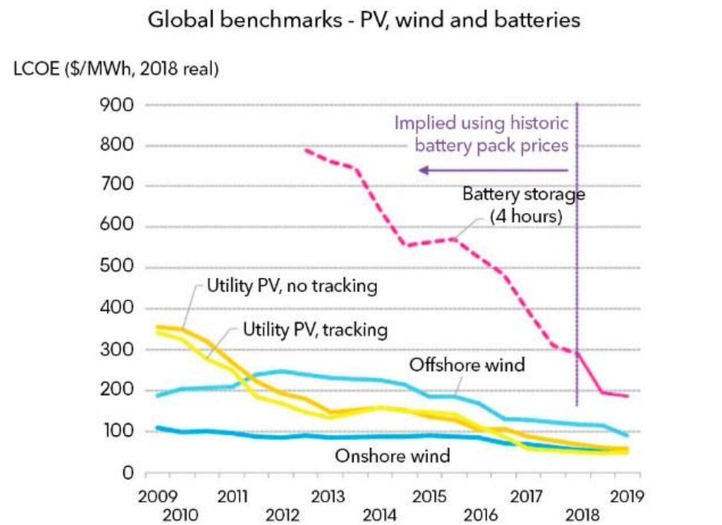
Two of the most crucial issues in distribution systems:

1. Severe peak-valley load difference; 2. distributed renewable energy integration)

- **Battery energy storage systems (BESS) mitigate these challenges:** the ability to dynamically switch between power generation and load.
- ESS's shorter duration applications (less than 4 hours) remain the most cost-efficient.



Source: BloombergNEF. Note: The global benmark is a country weighed-average using the latest annual capacity additions. The storage LCOE is reflective of a utility-scale Li-ion battery storage system running at a daily cycle and includes charging costs assumed to be 60% of whole sale base power price in each country.

Background:

- The price of batteries has decreased a lot;
- ESS is proved to have a startling decline speed in levelized cost of energy (LCOE).

✓ ESSs have obtained widespread application in distribution systems these years, and the potential revenue from ancillary services can further improves the profits of ESS investment

Motivations

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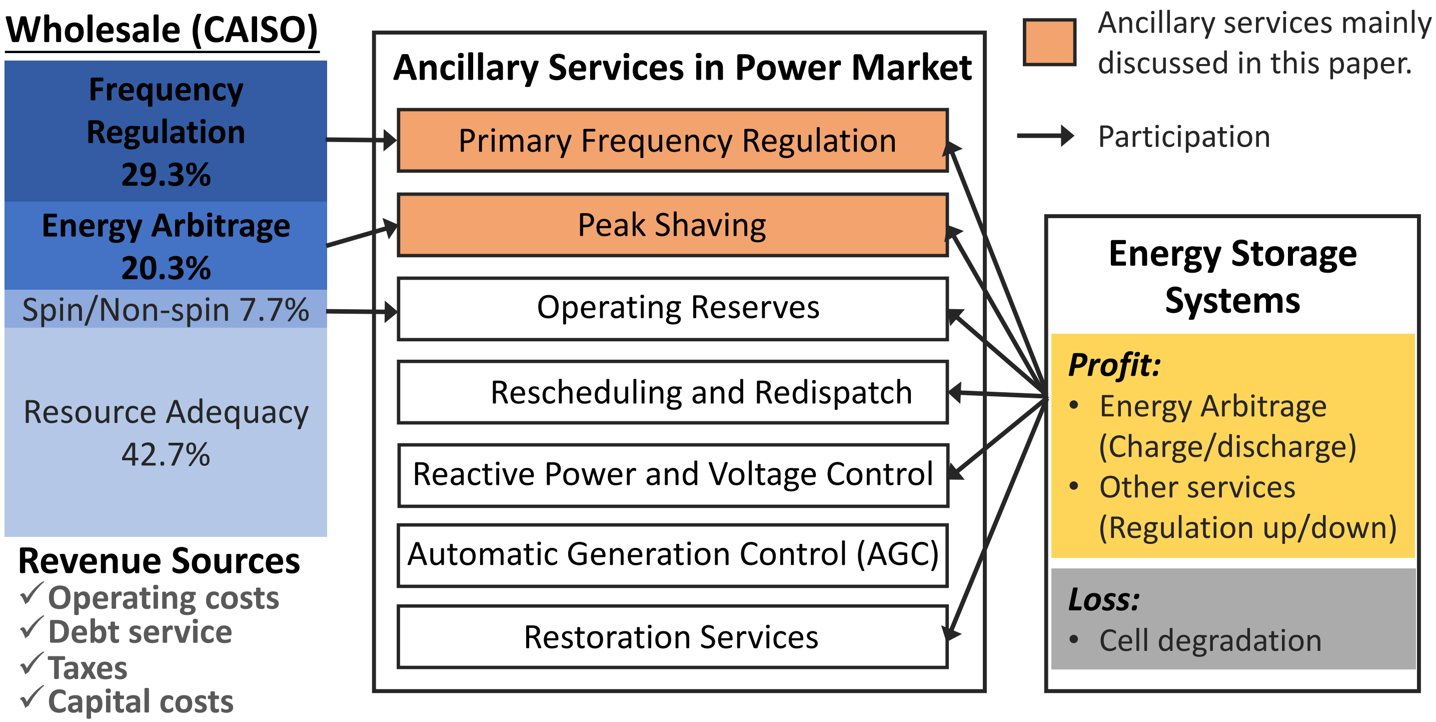
➢ Overview of the relationship between power ancillary service market and ESS



*Data Source: Lazard's Levelized Cost of Storage Analysis Version 4.0

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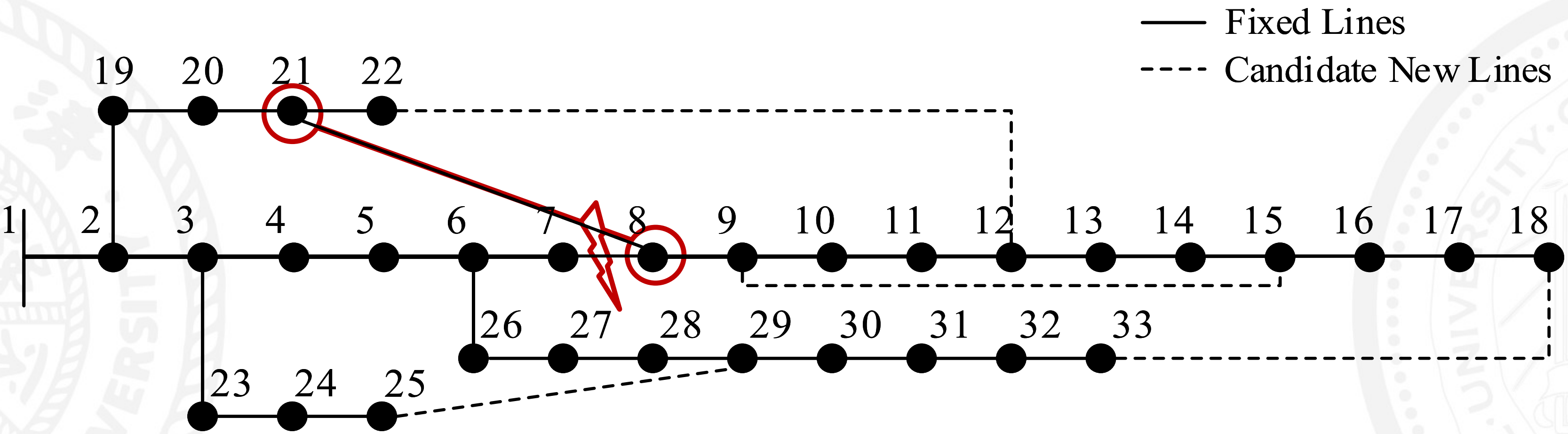
System Description

Network Configuration:

- **Based on IEEE 33-node distribution system.**
- **32 solid lines: fixed branches; 5 dotted lines: candidate new lines. The topology can be changed.**
- **No isolated node and no loop are allowed in the final network topology.**



Other Facilities:

- **Candidate nodes of ESS siting: the rest 32 nodes except the first one (slack bus).**
- **Substation construction: built at node 1, with three type options to select.**

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Mixed Integer Programming

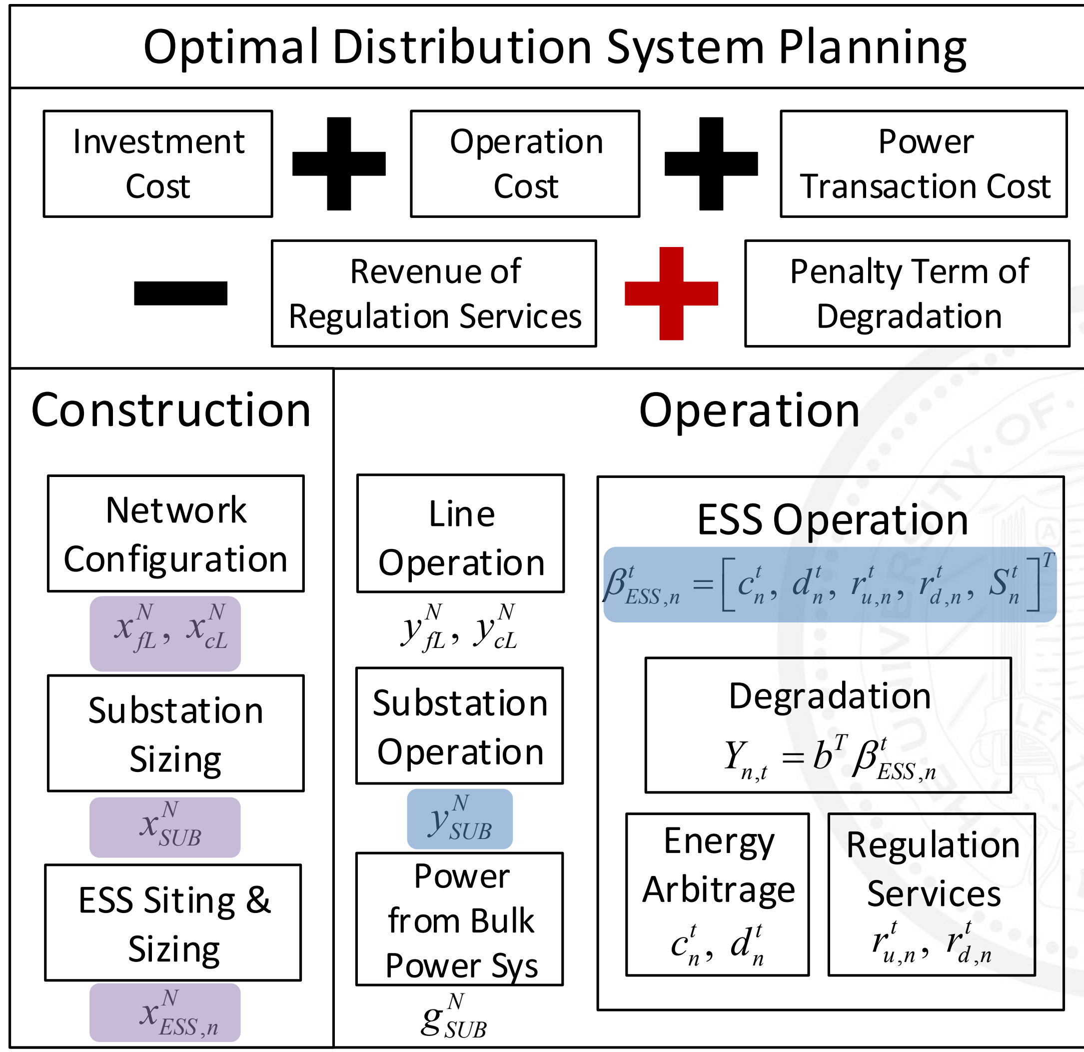
➢ **Overview of the MIP model**

Decision Variables:

- ☐ **Construction Stage:**
  x: vectors of binary variable. Determine whether to invest the facilities or not.

- ☐ **Operation Stage:**
  y: vectors of binary variable. Determine whether the facilities is operating or not.

  β: a vector of continuous variable related to ESS. Including charge/discharge, regulation up/down and state of charge (SOC).



Objective Function

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From the Perspective of Distribution System

(SUB: substation; ESS: energy storage system; LINE: transmission line.)

min Investment and Operation cost (SUB, ESS, LINE) + Power transaction cost (SUB) – Revenue of regulation services (ESS) + Penalty term of degradation (ESS)

Four Components in Detail:

$$C_{INV} + C_{OPE} = \sum_{fL} C_{fL}^{N} \cdot x_{fL}^{N} + \sum_{cL} C_{cL}^{N} \cdot x_{cL}^{N} + C_{SUB}^{N} \cdot x_{SUB}^{N} + \sum_{n} C_{ESS,n}^{N} \cdot x_{ESS,n}^{N} + \sum_{fL} O_{fL}^{N} \cdot y_{fL}^{N} + \sum_{cL} O_{cL}^{N} \cdot y_{cL}^{N} + O_{SUB}^{N} \cdot y_{SUB}^{N} + \sum_{n} O_{ESS,n}^{N} \cdot y_{ESS,n}^{N}$$

fL: fixed lines;
cL: candiadate new lines

$$C_{PT} = \sum_{s} \theta_s \sum_{t=0}^{T} L_{SUB,s}^{t} g_{SUB,s}^{t,N}$$

Power is bought from the bulk power system and denoted as actual power transmitted by the substation.

$$C_{REG} = \sum_{s} \theta_s \sum_{t=0}^{T} \sum_{n} \left(C_{REG,u,s}^{t} \cdot r_{u,n}^{t} + C_{REG,d,s}^{t} \cdot r_{d,n}^{t} \right)$$

r_u and r_d are nonnegative decision variables

$$C_{Deg} = \sum_{t=0}^{T} \sum_{n} M_{t}^{\deg} \cdot b^{T} \beta_{ESS,n}^{t}$$

A linear term reflecting degradation rates of ESS is added as a penalty to punish high degradation

Constraints

Constraints for Distribution System [2]

- Kirchhoff's current law (KCL):
$$S^{fL} I_{s,t}^{fL} + S^{cL} I_{s,t}^{cL} + r_{s,t} + g_{s,t} = d_{s,t} + d_t^{ESS} - c_t^{ESS} + p_t^u r_t^u - p_t^d r_t^d$$
- Generated power constraint: $0 \le g_{s,t}^{SUB,N} \le g_{\max}$
- Node voltage limits: $U_{\min} \le U_{s,t} \le U_{\max}$
- Feeders' capacity:
$$\begin{cases} \left| I_{s,t}^{fL} \right| \le \sum_{fL} y_{fL}^{N} \cdot I_{fL}^{\max} \\ \left| I_{s,t}^{cL} \right| \le \sum_{cL} y_{cL}^{N} \cdot I_{cL}^{\max} \end{cases}$$
- Construction logical constraints:
$$\begin{cases} \sum_{n} x_{ESS,n}^{N} \le 1, \ \sum x_{SUB}^{N} = 1 \\ y_{ESS,n}^{N} \le x_{ESS,n}^{N}, \ y_{SUB}^{N} \le x_{SUB}^{N} \\ \sum_{fL} y_{fL}^{N} + \sum_{cL} y_{cL}^{N} = 32 \end{cases}$$

✓ Building redundant project is not allowed.
✓ Facilities will only be available after construction.
✓ No isolated node and loop will exist in distribution network.

[2] Shen X. Expansion planning of active distribution networks with centralized and distributed energy storage systems[J]. IEEE Transactions on Sustainable Energy, 2017; 8:126-134.

Constraints

Planning and operation constraints for ESS [3]

$$S_{t+1}^{ESS} = S_t^{ESS} - \left(d_t^{ESS} - c_t^{ESS} + p_t^u r_t^u - p_t^d r_t^d\right)$$
$$t = 1, 2, \cdots, 23$$

Update equation for the ESS's state of charge

$$\begin{cases} 0 \le S_{t,n}^{ESS} \le E_{\max,n}^N \\ \left(r_t^d + c_t^{ESS}\right) \cdot (1\ hr) \le E_{\max}^N - S_t^{ESS} \\ \left(r_t^u + d_t^{ESS}\right) \cdot (1\ hr) \le S_t^{ESS} \end{cases}$$

The fact that the ESS's capacity must be partitioned.
These constraints ensure that no physical constraint is violated even when all of the committed regulation capacity is used.

$$\begin{cases} p_t^u r_t^u + d_t^{ESS} - p_t^d r_t^d \le P_{\max,n}^N,\ p_t^d r_t^d + c_t^{ESS} - p_t^u r_t^u \le P_{\max,n}^N \\ r_t^u + d_t^{ESS} \le P_{\max,n}^N,\ r_t^d + c_t^{ESS} \le P_{\max,n}^N \end{cases}$$

The ESS's total output power is constrained

$$S_t^{ESS} = S_0, \quad t = 1, 24$$

The ESS's initial state of charge

$$c_t^{ESS}, d_t^{ESS}, r_t^u, r_t^d \ge 0$$

Nonnegative decision variables

[3] Foggo B, Yu N. Improved battery storage valuation through degradation reduction[J]. IEEE Transactions on Smart Grid, 2017; 9:5721-5732.

Constraints

Decision variable relaxation

Degradation term in Objective functions: $C_{Deg} = \sum_{t=0}^{T}\sum_{n} M_t^{\deg} \cdot b^T \beta_{ESS,n}^t$

$$b = \begin{bmatrix} \frac{a_2}{4}(1-p_z) \\ \frac{a_2}{4}(1-p_z) \\ \frac{a_1^2 p_z}{2a_2} y_{ESS,n}^N P_{\max}^N \left(1.5\sigma_{t,u}^2 - 0.5\sigma_{t,d}^2 - p_u^t p_d^t\right) \\ \frac{a_1^2 p_z}{2a_2} y_{ESS,n}^N P_{\max}^N \left(1.5\sigma_{t,d}^2 - 0.5\sigma_{t,u}^2 - p_u^t p_d^t\right) \\ 0 \end{bmatrix} \times \begin{bmatrix} c_n^t \\ d_n^t \\ r_{u,n}^t \\ r_{d,n}^t \\ S_n^t \end{bmatrix} = \beta_{ESS,n}^t$$

Leads to nonlinearity!

A big M method (penalty factor method):

Replace: $\begin{cases} y_{ESS,n}^N \cdot r_{u,n}^t \\ y_{ESS,n}^N \cdot r_{d,n}^t \end{cases}$ Relax $\begin{cases} \Pi_{u,n}^{N,t} \\ \Pi_{d,n}^{N,t} \end{cases}$

Product of two decision variables

New variables

$$\Pi_{u,n}^{N,t} \le r_{u,n}^t, \quad \Pi_{d,n}^{N,t} \le r_{d,n}^t$$

$$\begin{cases} r_{u,n}^t \le \Pi_{u,n}^{N,t} + M \cdot \left(1 - y_{ESS,n}^N\right) \\ 0 \le \Pi_{u,n}^{N,t} + M \cdot y_{ESS,n}^N \end{cases}$$

$$\begin{cases} r_{d,n}^t \le \Pi_{d,n}^{N,t} + M \cdot \left(1 - y_{ESS,n}^N\right) \\ 0 \le \Pi_{d,n}^{N,t} + M \cdot y_{ESS,n}^N \end{cases}$$

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Typical Options

Options for Facilities in the Distribution System

➢ In this distribution system, the maximal amount of newly-built ESS is **4**. And the type options of the substation, ESSs and lines are given below：

Facilities	Different Options		
	Candidate nodes	Capacity (MW/A)	Construction cost (10^4US$)
SUB	1	5	8
		10	12
		15	15
ESS	2-33	2	30
		4	60
		8	119
Line	1-33	300	Affected by distances of 32 circuits.
		500	
		800	

Planning Results

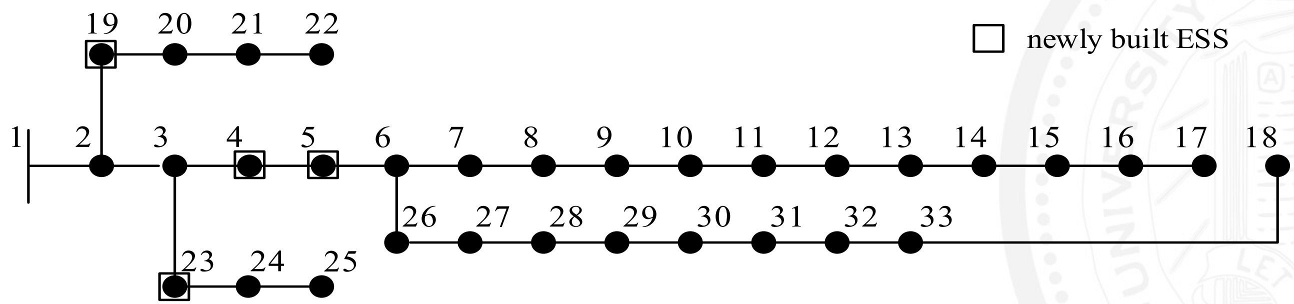
Two Groups of Control Experiments

Planning Periods: 15 years.

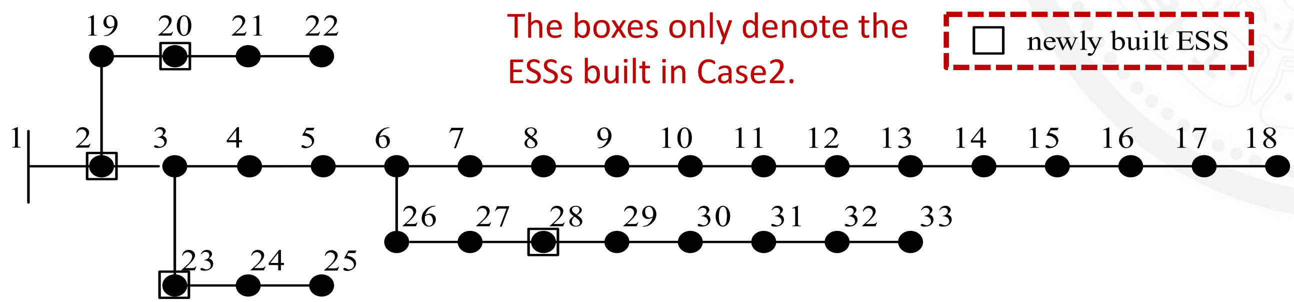
- Case1: Both regulation services and degradation penalty term of ESS are calculated in the model; (the optimal/control group)
- Case2: Degradation penalty term is ignored;
- Case3: Regulation services of ESS are ignored.

} (two experimental groups)

- Final network topology in Case1:



- Final network topology in Case2(3):



Economic analysis

From the Difference in Network Topology

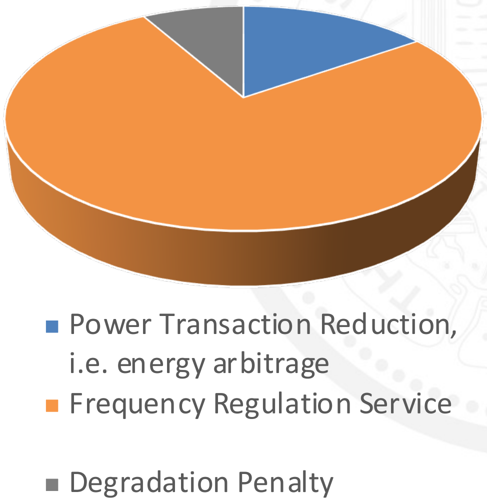
No ESS will be built in Case3 since the revenue from regulation services is crucial to the investment efficiency of ESS.

Economic Parameters in Different Cases

All the expenses constituting the objective function are listed which serve as economic parameters in each case.

Terms (10^4US$)	Case1	Case2	Case3
Total cost	4331.08	4261.12	4513.72
Investment cost of lines	27.09	27.12	27.12
Investment cost of SUB	8	8	8
Investment cost of ESS	476	476	0
Total Investment cost	511.09	511.12 ↑	35.12
Total operation cost	39.30	39.30	11.70
Power transaction cost	4341.50	4344.50 ↑	4466.90
Regulation services revenue	628.28	633.80	0
Degradation penalty	67.47	0	0

Benefit Analysis of Case1



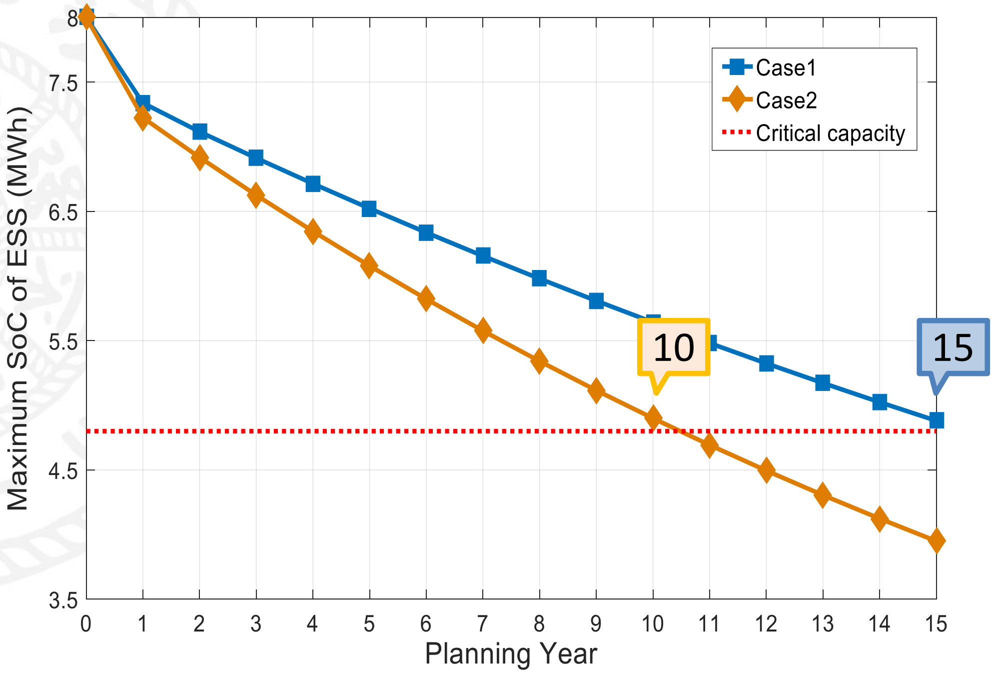
Comparison of ESS degradation

Degradation of ESS Capacity:

$$E_{\max}^{(n+1)} = r_1 e^{-r_2 \sum_{\eta=1}^{n} \deg_\eta} + (1-r_1) e^{\sum_{\eta=1}^{n} \deg_\eta}$$

- Threshold of ESS remaining capacity for the DSO to end its use is set as **60%** of the nominal value.

Rules of degradation behaviors:



Findings:

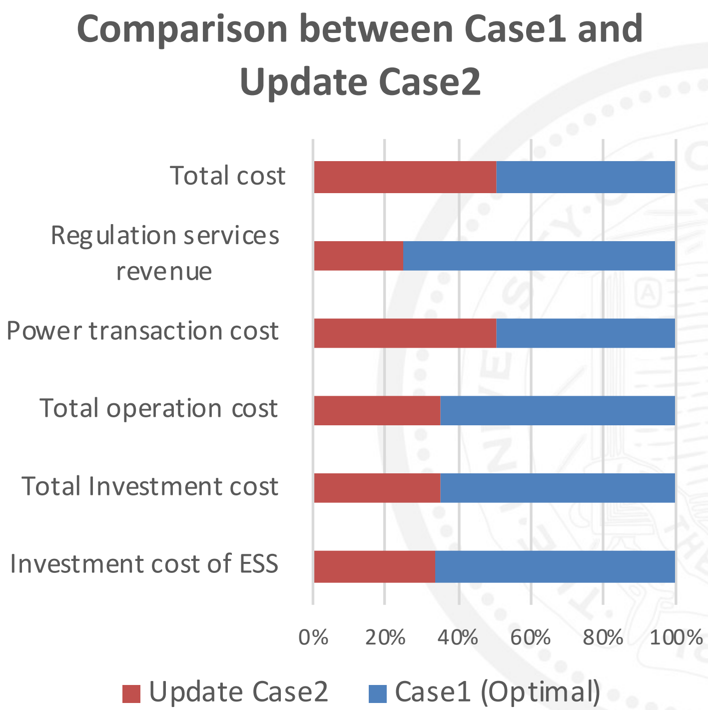
- ✓ ESSs in Case1 can be in operation during the whole planning period.
- ✓ ESSs in Case2 actually work for 10 years, and the planning results need to be updated.

Comparison of ESS degradation

Preliminary and Actual Planning Results of Case2

In Case2, the ESSs will operate in the first decade and stopped for the left five years.

Terms (10^4US$)	Original	Update	Case1 (Optimal)
Total cost	4261.12	4490.28	4331.08
Investment cost of lines	27.12	27.09	27.09
Investment cost of SUB	8	8	8
Investment cost of ESS	476	238 ↓	476
Total Investment cost	511.12	273.09	511.09
Total operation cost	39.30	21.10	39.30
Power transaction cost	4344.50	4406.50 ↑	4341.50
Regulation services revenue	633.80	210.41 ↓	628.28



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Conclusions

Overall Planning Cost ⟷ Co-optimize ⟷ Degradation Behaviors

Three cases (Case1 is the optimal):

- ☐ Case2 **(No degradation penalty)** weeds out ESSs **five years** earlier thus being less economical than the optimal case.
  Co-optimizing degradation behaviors will prolong ESS's lifespan.
- ☐ Case3 **(No regulation services)** reaches the highest overall planning cost on account of no ESS being built.
  Revenue from regulation services is a decisive factor for the profitability of ESS.

- Both revenue of regulation services and degradation term included in the objective function do help to extend ESS lifetime as well as maximizing economic profits of the distribution system.

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Thanks!
Q&A