Practical Operations of Energy Storage Providing Ancillary Services: From Day-Ahead to Real-Time

Preprint

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Practical Operations of Energy Storage Providing Ancillary Services: From Day-Ahead to Real-Time

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***Abstract*—As renewable resources are increasingly penetrating power systems, energy storage systems (ESSs) become essential in providing both energy arbitrage and ancillary services. Because of its high flexibility, ESSs have been taken into account in the daily operation of the bulk power system in many places. This paper proposes a general framework in the current electricity market environment to help system operators model the participation of multi-type ESSs and evaluate the performance of both energy arbitrage and reserve provision. We discuss different levels of ESSs' flexibility in providing ancillary services and also consider a deliberate and practical implementation of the modeling. This framework can be seamlessly integrated into the daily market operation without sacrificing computational efficiency. Numerical experiments validate the efficacy of the proposed framework and show that ESSs possess excellent potential in providing ancillary services for the bulk power system.**

***Index Terms*—Energy storage system, electricity market operation, renewable, ancillary services.**

I. NOMENCLATURE

1) *Indices*:

g / r / i	Thermal generator/renewable generator/ESS
ℓ	Line
b	Bus
t	Time

2) *Parameters*:

$P_{(g,r)}^{\max}/P_{(g,r)}^{\min}$	Maximum/minimum dispatch limit for thermal/renewable units
SU_g / SD_g	Startup/Shutdown cost for generator g
$RU_{(g,i)}$	Ramp-up limit of generator g/ESS i
$RD_{(g,i)}$	Ramp-down limit of generator g/ESS i
$T_g^{\text{min(ON,OFF)}}$	Minimum ON/OFF time of generator g
SC	Load-shedding penalty cost
$GSF_{\ell,b}$	Generation shift factor from bus b to line ℓ
FL_ℓ	Thermal flow limit of line ℓ
$CH_i^{\max}$	Maximum charging limit for ESS i
$DIS_i^{\max}$	Maximum discharging limit for ESS i
$SOC_i^{\min}$	Minimum SOC limit for ESS i
$SOC_i^{\max}$	Minimum SOC limit for ESS i
LR_i	SOC loss rate of ESS i
η_i	Charging/discharging efficiency of ESS i
$T_{\text{agc}}^{\text{rec}}$ / $T_{\text{pfr}}^{\text{rec}}$	Reaction time for AGC/PFR
PFR_t^{req}	PFR capacity requirement at time t
$AGC_t^{\text{req-(up,dn)}}$	AGC-up/-down capacity requirement at time t
$\Delta f^{\max}/DB$	Maximum allowed frequency deviation/governor deadband
Req_g	Equivalent droop coefficient of generator g

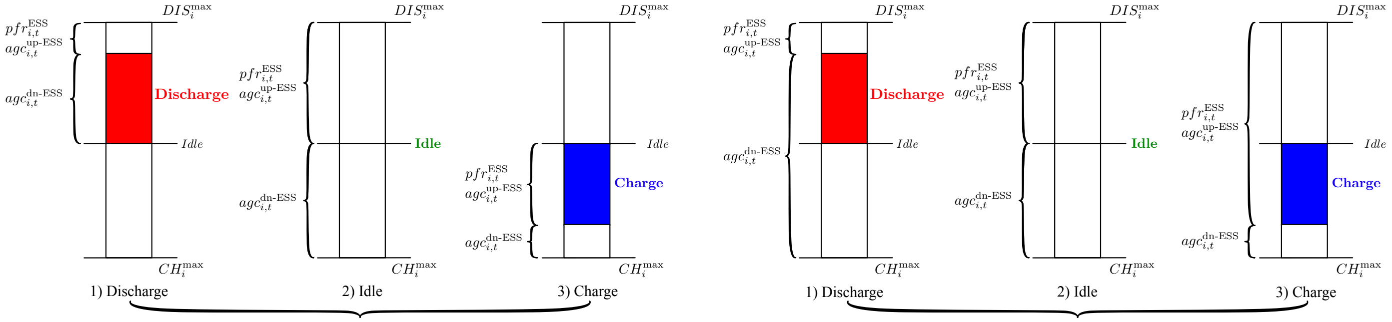
3) *Variables*:

$p_{(g,r,i),t}$	Active power of generator g/r/ESS i at t
$u_{g,t}$ / $v_{g,t}$	Startup/Shutdown status of generator g at t
$w_{g,t}$	Unit commitment of generator g at t
$pfr_{(g,r),t}$	Procured PFR from generator g/r at t
$agc_{(g,r),t}^{\text{(up,dn)}}$	Procured AGC-up/-down from generator g/r at t
$ls_{b,t}$	Curtailed load of bus b at t
$c_{i,t}$ / $d_{i,t}$	Charging/discharging status of ESS i at t
$ch_{i,t}$ / $dis_{i,t}$	Charging/discharging power of ESS i at t
$soc_{i,t}$	SOC of ESS i at t
$pfr_{i,t}^{\text{ESS}}$	Procured PFR from ESS i at t
$agc_{i,t}^{\text{(up/dn)-ESS}}$	Procured AGC-up/-down from ESS i at t

II. INTRODUCTION

The increasing penetration of renewables has called for new solutions and operation schemes to deal with the associated uncertainty and variability. Energy storage systems (ESSs) have been widely discussed in both industry and academia as a potential solution to equalize renewable uncertainties in bulk power systems [1]–[3]. It is well-known that ESSs are viable in assisting energy scheduling affected by the uncertain nature of renewable units. Further, ESSs could exploit their flexibility to provide ancillary services (ASs), which can alleviate the burden of reserve requirements.

There are many types of ESSs. The battery energy storage system ESS (BESS) and the pumped hydroelectric energy storage system (PESS) are the most widely discussed. A PESS harvests or releases electric power by pumping between different reservoir levels, and the pumping operation is often hourly [3]. A BESS is comparatively much more flexible than a PESS because the fast-response battery can easily switch statuses [4], which is beneficial in the provision of fast frequency response. Most BESSs are equipped with controllable inverters that can help settle the scheduled power dispatch and allocate reserve capacity very quickly; hence, the differences between ESSs' flexibilities should be thoroughly considered in practical electric market operation.



(a) PESS Operation (b) BESS Operation

Fig. 1. Two schemes for ESSs providing ASs.

Many existing works have already been conducted on the optimal operation of ESSs in the energy and reserve market. R. Khatami *et al.* [5] considered a mixed-integer linear programming (MILP) model for the air compressor ESSs in the energy market with the regulation service. N. Cobos *et al.* [6] proposed a robust optimization model for ESSs participating in the co-optimized energy and AS market. N. Padmanabhan *et al.* [7] developed a cost-based optimization framework for ESSs in the energy and spinning reserve market. None of the existing works, however, have fully investigated the flexibility of ESSs, and the capability of providing ASs from different types of ESSs has not been well studied.

To better study different flexibility types of ESSs, we propose a flexible operation scheme that provides AS regardless of its charging/discharging status to acknowledge the fast response of BESSs. We also consider a relatively inflexible scheme that can provide AS but with a reduced capability to represent PESSs. We verify the proposed ESS flexibility schemes in a multi-timescale electric market operation framework consisting of day-ahead unit commitment (DAUC), real-time unit commitment (RTUC), and real-time economic dispatch (RTED). The framework considers the look-ahead rolling horizon, generators' startup/shutdown trajectory modeling, and ESS interpolation to mimic a realistic market operation respecting the U.S. independent system operator (ISO)'s practice.

The main contributions of this work are twofold: 1) we propose two operation schemes for ESSs providing both energy and ASs considering their flexibilities by leveraging MILP techniques; 2) we test the proposed schemes in a practical market operation model, and we use the case studies to compare effectivenesses of different types of ESSs in a system under high renewable penetration.

III. TWO OPERATION SCHEMES FOR ESSS

In this section, we introduce how we use the MILP technique to develop the two operation schemes for ESSs with different flexibilities. The AS types within the scope of the study include the primary frequency response (PFR) and the secondary regulation service (often denoted as automatic generation control, AGC) that can be provided by both generators and ESSs. We innovatively consider three operating modes of ESSs: charging, discharging, and idle. Regulation services are divided by the regulation-up and regulation-down, the first of which can be provided by the headroom of units, and the dispatch can cover the second. In most situations, PFR is also considered as a frequency-up service [8].

A. General ESS Operating Constraints

We start from the general ESS model [9], which is valid for both PESSs and BESSs. It constrains ESS power output (1a), three operating modes (1b), ESS ramping (1c)-(1d), ESS charging/discharging (1e)-(1f), state-of-charge (SOC) (1g), and SOC limits with ASs (1h)-(1i). We defer the charging/discharging constraints with ASs to the next two subsections.

$$p_{i,t} = dis_{i,t} - ch_{i,t}, \tag{1a}$$

$$c_{i,t} + d_{i,t} \leq 1, \tag{1b}$$

$$p_{i,t} - p_{i,t-1} + agc_{i,t}^{\text{up-ESS}} + pfr_{i,t}^{\text{ESS}} \leq RU_i, \tag{1c}$$

$$p_{i,t} - p_{i,t-1} - agc_{i,t}^{\text{dn-ESS}} \geq -RD_i, \tag{1d}$$

$$ch_{i,t} \leq c_{i,t} \cdot CH_i^{\max}, \tag{1e}$$

$$dis_{i,t} \leq d_{i,t} \cdot DIS_i^{\max}. \tag{1f}$$

$$soc_{i,t} - soc_{i,t-1} \cdot (1 - LR_i) = ch_{i,t} \cdot \eta_i - dis_{i,t}/\eta_i, \tag{1g}$$

$$soc_{i,t} + agc_{i,t}^{\text{dn-ESS}} \cdot T_{\text{agc}}^{\text{rec}} \leq SOC_i^{\max}, \tag{1h}$$

$$soc_{i,t} - agc_{i,t}^{\text{up-ESS}} \cdot T_{\text{agc}}^{\text{rec}} - pfr_{i,t}^{\text{ESS}} \cdot T_{\text{pfr}}^{\text{rec}} \geq SOC_i^{\min}. \tag{1i}$$

B. PESS: Low-Flexibility Scheme

As the hourly pumping between reservoirs restrains the ramping of PESS power, PESSs can provide ASs based on its current status. For example, when the PESS is discharging, it could be regarded as a supplying unit, whose headroom can provide frequency-up service and dispatch can provide frequency-down, and *vice versa*. Fig. 1 (a) depicts the operation logic of this flexibility type, and constraints (2a)-(2b) provide an exact formulation that realizes the scheme. Note that the PFR and AGC-up capacities share the same headroom of ESSs because both are frequency-up services.

$$pfr_{i,t}^{\text{ESS}} + agc_{i,t}^{\text{up-ESS}} \leq (1 - c_{i,t}) \cdot DIS_i^{\max} + ch_{i,t} - dis_{i,t}, \tag{2a}$$

$$agc_{i,t}^{\text{dn-ESS}} \leq (1 - d_{i,t}) \cdot CH_i^{\max} + dis_{i,t} - ch_{i,t}. \tag{2b}$$

As shown in Fig. 1 (a), when the PESS is charging, $dis_{i,t}$ is 0, $c_{i,t}$ is 1, $d_{i,t}$ is 0, the headroom is the charging power, and the limit of charging caps the frequency-down; when the PESS is discharging, $ch_{i,t}$ is 0, $c_{i,t}$ is 0, $d_{i,t}$ is 1, the headroom is the limit of discharging, and the discharging dispatch provides the frequency-down; when the PESS is idle, $dis_{i,t}$, $ch_{i,t}$, $c_{i,t}$, and $d_{i,t}$ are all 0, and the AS can be procured according to the up and down limits of PESSs. We can see that (2a) and (2b) represent all the operating scenarios exactly.

C. BESS: High-Flexibility Scheme

As a fast-response unit, a BESS can quickly switch charging/discharging statuses, which makes it possible to provide ASs not only from the current direction of power but also from the opposite direction. Fig. 1 (b) shows the operation logic, and constraints (3a) and (3b) realize the scheme.

$$pfr_{i,t}^{\text{ESS}} + agc_{i,t}^{\text{up-ESS}} \leq DIS_i^{\max} + ch_{i,t} - dis_{i,t}, \tag{3a}$$

$$agc_{i,t}^{\text{dn-ESS}} \leq CH_i^{\max} + dis_{i,t} - ch_{i,t}. \tag{3b}$$

Referring to Fig. 1 (b), similar reasonings can be deduced as in the PESS case, and we find that (3a) and (3b) can exclude all binary decision variables without sacrificing the exactness of the formulation. The essence of using (3a) and (3b) is that we fully exploit the flexibility and fast response of BESSs in providing frequency services.

IV. MARKET OPERATIONS WITH ESS SCHEMES

In this section, we discuss the practical market operation framework that accommodates the proposed ESS schemes. The framework includes the classic DAUC, RTUC, and RTED that respect the operation practice of U.S. ISOs. For brevity, we only present the DAUC formulation in Section IV-A, and we discuss the multi-timescale workflow in Section IV-B.

A. Operation Formulation

We adopt the typical UC formulation from [10], whereas the model of the generators' AS provision follows [8].

$$u_{g,t} + v_{g,t} \leq 1, \tag{4a}$$

$$w_{g,t} - w_{g,t-1} \leq u_{g,t} - v_{g,t}, \tag{4b}$$

$$\sum_{\tau=t-T_g^{\text{minON}}+1}^{t} u_{g,\tau} \leq w_{g,t}, \tag{4c}$$

$$\sum_{\tau=t-T_g^{\text{minOFF}}+1}^{t} v_{g,\tau} \leq 1 - w_{g,t} \tag{4d}$$

$$p_{g,t} - p_{g,t-1} + pfr_{g,t} + agc_{g,t}^{\text{up}} \leq RU_g, \tag{4e}$$

$$p_{g,t-1} - p_{g,t} - agc_{g,t}^{\text{dn}} \geq -RD_g, \tag{4f}$$

$$p_{(g,r),t} - agc_{(g,r),t}^{\text{dn}} \geq w_{(g,r),t} P_{(g,r)}^{\min}, \tag{4g}$$

$$p_{(g,r),t} + pfr_{(g,r),t} + agc_{(g,r),t}^{\text{up}} \leq w_{(g,r),t} P_{(g,r)}^{\max}, \tag{4h}$$

$$pfr_{g,t} \leq (\Delta f^{\max} - DB)/Req_g, \tag{4i}$$

$$agc_{g,t}^{\text{dn}} \leq RD_g \cdot T_{\text{agc}}^{\text{rec}}, \tag{4j}$$

$$agc_{g,t}^{\text{up}} \leq RU_g \cdot T_{\text{agc}}^{\text{rec}}. \tag{4k}$$

$$\sum_g p_{g,t} + \sum_r p_{r,t} + \sum_i p_{i,t} = \sum_b D_{b,t} - ls_{b,t}, \tag{4l}$$

$$\sum_g pfr_{g,t} + \sum_r pfr_{r,t} + \sum_i pfr_{i,t}^{\text{ESS}} \geq PFR_t^{\text{req}}, \tag{4m}$$

$$\sum_g agc_{g,t}^{\text{up}} + \sum_r agc_{r,t}^{\text{up}} + \sum_i agc_{i,t}^{\text{up-ESS}} \geq AGC_t^{\text{req-up}}, \tag{4n}$$

$$\sum_g agc_{g,t}^{\text{dn}} + \sum_r agc_{r,t}^{\text{dn}} + \sum_i agc_{i,t}^{\text{dn-ESS}} \geq AGC_t^{\text{req-dn}}, \tag{4o}$$

$$\begin{aligned} - FL_\ell \leq & \sum_{g \in LG} GSF_{\ell,g} p_{g,t} + \sum_{r \in LR} GSF_{\ell,r} p_{r,t} \\ & + \sum_{i \in LI} GSF_{\ell,i} p_{i,t} - \sum_{b \in LB} GSF_{\ell,b} D_{b,t} \leq FL_\ell. \end{aligned} \tag{4p}$$

The model constrains the UC decisions (4a)-(4b), minimum ON/OFF time (4c)-(4d), ramping (4e)-(4f), dispatch with ASs (4g)-(4h), PFR and AGC physical limits (4i)-(4k) [8], load balance (4l), AS requirements (4m)-(4o), and DC power flow (4p). Note that we slightly abuse the notation where $P_r^{\max}$ in (4h) is actually a time series of forecasted renewable outputs.

Then we present the objective and the overall model as follows.

$$\begin{aligned} \min \sum_t \Big\{ & \sum_g [SU_g u_{g,t} + SD_g v_{g,t} + f_c(p_{g,t})] + SC \cdot \sum_b ls_{b,t} \\ & + f_a(pfr_{(g,r,i),t}, agc_{(g,r,i),t}^{\text{up}}, agc_{(g,r,i),t}^{\text{dn}}) \Big\}, \\ s.t. \quad & \text{Constraints (1), (4), (2)/(3),} \end{aligned}$$

where f_c is the piecewise linear cost function of the generators, and f_a is the linear cost function of the AS procurements.

B. Practical Multi-Timescale Workflow

To capture the realistic market operation, we show the proposed 24-hour multi-timescale workflow of DAUC, RTUC, and RTED. Fig. 2 details the workflow procedure.

Step 1. DAUC Simulation. We first solve a 24-hour DAUC. Because the energy arbitrage should be captured in day-ahead operations, we fix all the ESS dispatches by using minute-level interpolations over the DAUC results for the RTUC and RTED; however, the AS from ESSs is still dispatch-able therein.

Step 2. RTUC Simulation. We solve the hourly rolling-horizon-based RTUC with a 3-hour look-ahead horizon. The formulation is similar to (4), but we commit only flexible units, whose startup/shutdown durations are less than 1 hour.

Step 3. RTED Simulation. Based on DAUC and RTUC results, we build the generators' startup and shutdown trajectories and update $P_g^{\max}$ and $P_g^{\min}$. More details about the generator trajectory modeling can be found in [11]. We also fix the ESS dispatch in RTED by interpolating the ESS result in DAUC that considers energy arbitrage. Then we solve the RTED with a 5-minute resolution and a 2-hour look-ahead horizon.

V. NUMERICAL EXPERIMENTS

In this section, we verify the proposed ESS schemes and the practical market operation framework in an 18-bus system [12]. The system accommodates five generators, including a 1,500-MW photovoltaic (PV) power plant and a 300-MW/1,500-MWh ESS. Fig. 3 draws the topology. We solve all instances in Python 3.7 using Pyomo [13], and we employ Gurobi 9.0.1 as the solver. We cast four cases to validate the proposed framework.

- *Case 1.* No ESS is installed.
- *Case 2.* The ESS is installed but cannot provide ASs.
- *Case 3.* The ESS is installed and can provide ASs with the low flexibility as in model (2).

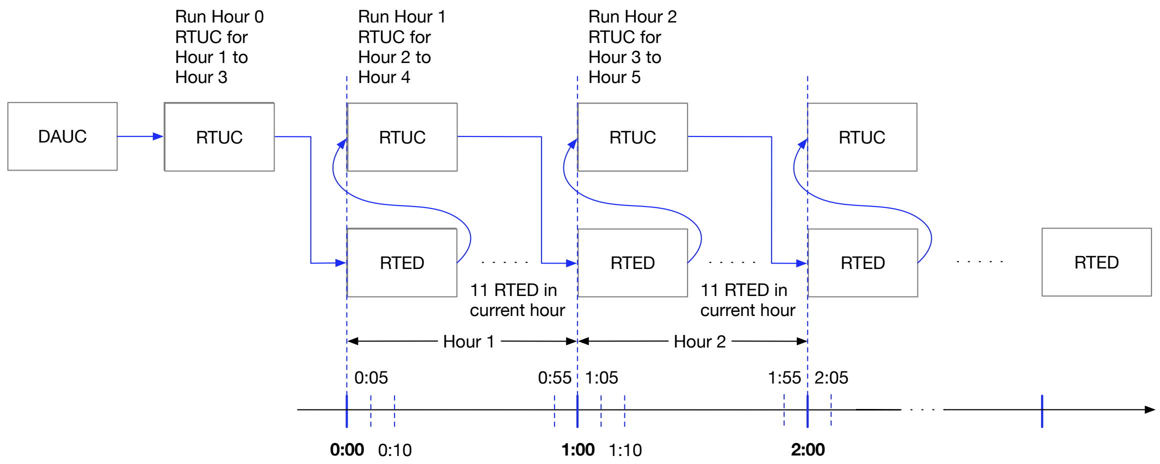


Fig. 2. Multi-timescale market operation workflow.

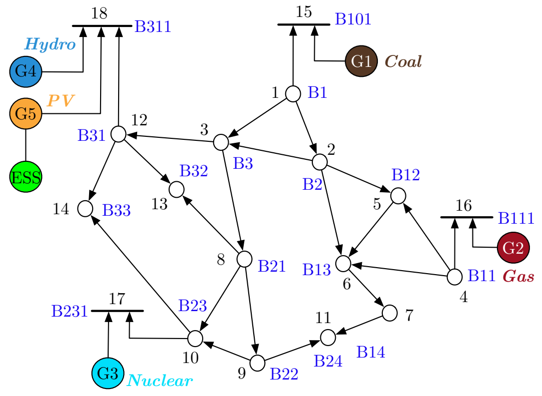


Fig. 3. 18-bus one-line diagram.

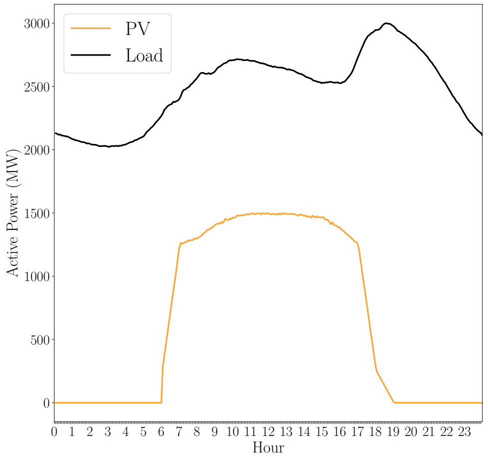


Fig. 4. Load and PV profiles.

- *Case 4.* The ESS is installed and can provide ASs with the high flexibility as in model (3).

In all cases, we consider the zero price of AS procurements for all stakeholders to compare cases in an equal-opportunity environment. Detailed AS pricing mechanisms for ESSs and generators are out of the scope of this paper and can be of future research interest. Based on dynamic simulation results, we consider a 7% transmission loss, set SC as \$100,000/MWh, and the peak PV penetration is 50%, whose profile is shown in Fig. 4 together with the load profile. The peak load is 1500 MW. Table I and Table II tabulate the detailed generator and ESS parameters, respectively. Note that for simplicity, we use one ESS in *Case 3* and *Case 4* to mimic PESSs and BESSs, respectively. The only difference between them is the AS modeling as discussed in Section III. However, for practical analysis on applications of PESSs and BESSs in real-world systems, they could differ in some parameters, *e.g.*, ramp rate, loss rate, and the minimum pumping time requirement for PESS. The PFR and AGC requirements are 1.9% and 5% of the load, respectively. Based on the generator flexibility, the DAUC commits G1-G4, the RTUC recommits G2 and G4, whereas the generators' trajectories are built linearly in the RTED according to the workflow in Section IV-B.

TABLE I
GENERATOR PARAMETERS

Unit	Cost ($/MW)	$P_g^{\max}$ (MW)	$P_g^{\min}$ (MW)	Ramp (MW/5min)	Min. ON (hr)	Min. OFF (hr)
G1	13.82	600	300	8	9	24
G2	19.79	1200	300	12	3	3
G3	1	600	50	18	1	1
G4	2	1200	1000	1	24	24
PV	0	1500	0	NA	NA	NA

TABLE II
ESS PARAMETERS

	ESS Capacity	Maximum SOC	Minimum SOC	Ch./Dis. Efficiency	Maximum Charge
ESS	1500 MWh	100%	6.6%	98%	300 MW
	Maximum Disharge	Initial Discharge	Initial SOC	Ramp rate	SOC loss rate
ESS	300 MW	150 MW	80%	50 MW/min	0

A. *ESS Effectiveness: Economic Assessment*

We first assess the economic aspects for ESSs participating in the co-optimized energy and AS market. Table III tabulates

TABLE III
DAUC ECONOMIC ASSESSMENT OF CASE STUDIES

	Case 1	*Case 2*	*Case 3*	*Case 4*
Total Cost ($)	293,473	269,008	256,407	255,399
PV Curtailment (MWh)	215.20	9.74	0	0
Highest LMP ($)	13.74	13.74	13.82	13.82

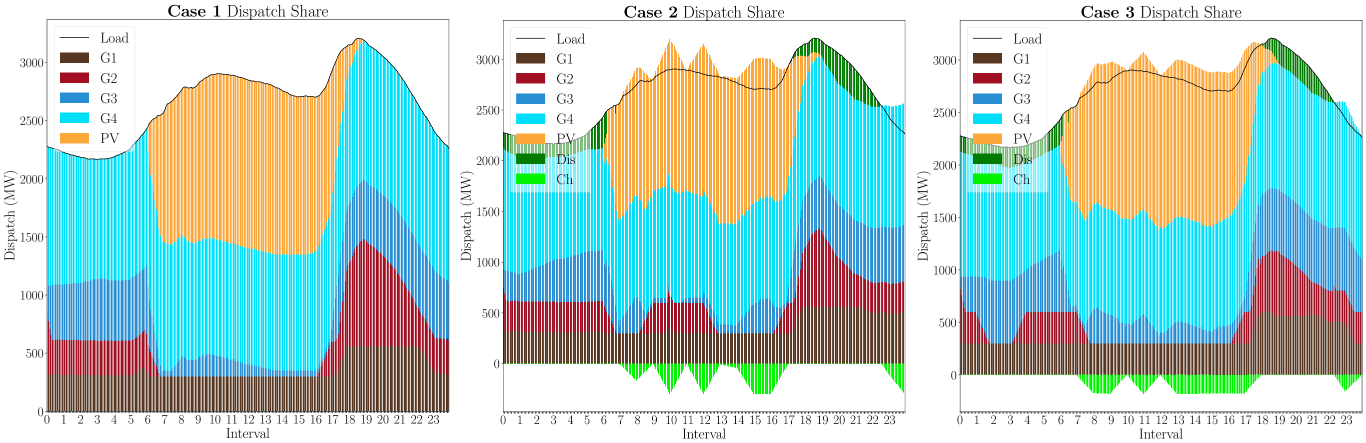


Fig. 5. RTED load sharing of *Case 1-3*.

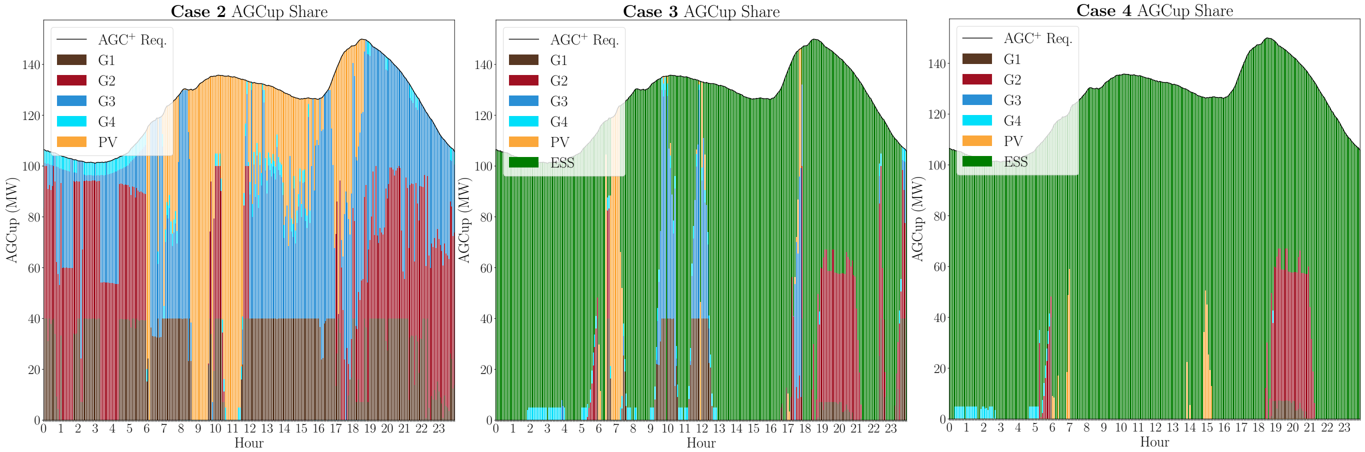


Fig. 6. AGC-up procurement in *Case 2-4*.

the system costs, PV curtailments, and system-level locational marginal prices (LMPs) for all cases in the DAUC. The LMP calculation considers the AS capacity components [8]. We observe that from *Case 1* to *Case 3*, installing ESSs in the system reduces the total system cost dramatically because ESSs carry out energy arbitrage, especially when PV is abundant. When ESSs can provide ASs, the benefit grows more salient because the generators are now free from AS requirements. From *Case 3* to *Case 4*, the ESS becomes more flexible, whereby the cost also falls similarly. Besides, the system LMP increases after the ESSs participate in the AS provision, implying that the ESSs foster a more competitive market environment.

B. *ESS Effectiveness: Energy Scheduling*

We further investigate how the ESS contributes to the economic dispatch via energy arbitrage and how it synergizes with renewables. Fig. 5 depicts the RTED dispatch results of the four cases. The operation costs of the thermal generators follow the ascending order of G3<G4<G1<G2. The nuclear unit (G4) has a low ramping limit and obeys a must-ON requirement. We interpolate the ESS dispatch in the RTED from the DAUC results. The optimized schedule of the RTED tells that the ESS gets charged in the daytime because the PV is abundant, and it is discharged in the peak load time when the PV power falls off. We can also see from *Case 1* to *Case 4* that, as the ESS participation increases, the dispatch of the marginal unit, *i.e.*, G2, decreases as well. Compared with *Case 1*, other cases are able to shut down G2 in the daytime to reduce the cost. For the impact on PV, we can conclude from Table III that the ESS participation helps the system accommodate more PV as the PV curtailment also decreases from *Case 1* to *Case 4*.

C. *ESS Effectiveness: Ancillary Service Provision*

We discuss how different ESS flexibilities affect the AS procurement for the system in this subsection. For system-level ASs, Fig. 6 compares the AGC-up provision between *Case 2*, *Case 3*, and *Case 4* in the RTED. We omit the discussion on PFR and AGC-down, the first of which has a similar pattern with the AGC-up because they share the same headroom, and the generators' dispatch can cover AGC-down services. When ESSs cannot provide ASs, generators reserve the headroom for frequency-up services, whereas the marginal unit G2 is most likely to save the headroom. Because the PV unit can use its curtailed power to provide AGC-up, PV and G2 are two main providers of AGC-up in *Case 2*. If we let the ESS provide ASs, the ESSs gain a huge advantage of providing AGC-up in that their high flexibilities render a much lower opportunity cost of providing such services. When the ESS becomes more flexible, it can cover even most of the AS provision if we compare *Case*

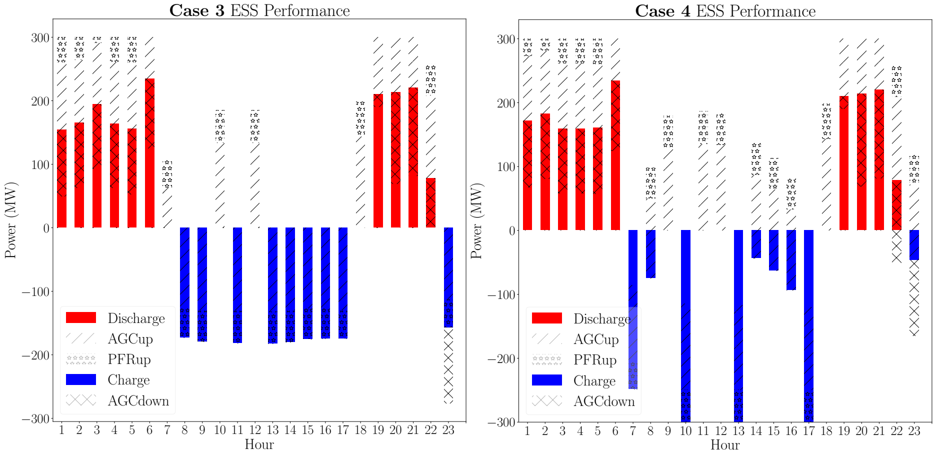


Fig. 7. ESS schedule in *Case 3* and *Case 4*.

3 amd *Case 4* in Fig. 6; hence, the ESS has the potential to take the major responsibility of frequency regulation and free other generators from the burden of providing such services.

We also compare the ESS dispatch of *Case 3* and *Case 4*. For better illustration, we depict their detailed DAUC performances in Fig. 7. We observe that the ESS in *Case 4* can cover more ASs than the ESS in *Case 3* as it can provide ASs by exceeding its opposite limits, because of its higher flexibility of switching conditions. It validates the exactness of the proposed ESS operating schemes and also gives a reason for the lower cost of *Case 4* in Table III, and hence system operators should consider the difference in ESS flexibilities during market operations.

VI. REMARKS

In this paper, we proposed two operating schemes of ESSs considering physical flexibilities and a practical market operation paradigm. We exactly model the AS provision of ESSs by MILP techniques without sacrificing computational efficiency. We also illustrate how ESSs exert impacts on the daily market operation of power systems under high renewable penetrations by evaluating them in a practical multi-timescale market framework. Upon installing ESSs, the system can reduce the operating cost, accommodate more PV power, and relieve the burden of the AS provisions of thermal units in a cost-effective fashion. Different flexibilities of ESSs, for instance as realized in PESSs and BESSs, contribute to the grid by providing both energy arbitrage and ASs in different levels, which have been thoroughly studied in this paper. Based on this work, we can also point out a future research direction of assessing different pricing mechanisms of ASs provided by conventional generation, renewables, and ESSs,.

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REFERENCES

[1] P. Denholm, J. Nunemaker, P. Gagnon, and W. Cole, "The Potential for Battery Energy Storage to Provide Peaking Capacity in the United States," tech. rep., National Renewable Energy Laboratory, June 2019.

[2] Y. Zhang, J. Wang, and Z. Li, "Uncertainty Modeling of Distributed Energy Resources: Techniques and Challenges," *Current Sustainable/Renewable Energy Reports*, vol. 6, no. 2, pp. 42–51, 2019.

[3] S. Koohi-Fayegh and M. Rosen, "A Review of Energy Storage Types, Applications and Recent Developments," *Journal of Energy Storage*, vol. 27, p. 101047, 2020.

[4] V. Gevorgian and D. Corbus, "Ramping Performance Analysis of the Kahuku Wind-Energy Battery Storage System," tech. rep., National Renewable Energy Laboratory, November 2013.

[5] R. Khatami, K. Oikonomou, and M. Parvania, "Look-Ahead Optimal Participation of Compressed Air Energy Storage in Day-Ahead and Real-Time Markets," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 2, pp. 682–692, 2020.

[6] N. G. Cobos, J. M. Arroyo, N. Alguacil, and J. Wang, "Robust Energy and Reserve Scheduling Considering Bulk Energy Storage Units and Wind Uncertainty," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5206–5216, 2018.

[7] N. Padmanabhan, M. Ahmed, and K. Bhattacharya, "Battery Energy Storage Systems in Energy and Reserve Markets," *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 215–226, 2020.

[8] E. Ela, V. Gevorgian, A. Tuohy, B. Kirby, M. Milligan, and M. O'Malley, "Market Designs for the Primary Frequency Response Ancillary Service—Part I: Motivation and Design," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 421–431, 2014.

[9] N. Li, C. Uçkun, E. M. Constantinescu, J. R. Birge, K. W. Hedman, and A. Botterud, "Flexible Operation of Batteries in Power System Scheduling With Renewable Energy," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 685–696, 2016.

[10] M. Carrion and J. M. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1371–1378, 2006.

[11] J. M. Arroyo and A. J. Conejo, "Modeling of start-up and shut-down power trajectories of thermal units," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1562–1568, 2004.

[12] Q. Wang, H. Wu, J. Tan, B. Hodge, W. Li, and C. Luo, "Analyzing the impacts of increased wind power on generation Revenue Sufficiency," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, pp. 1–5, 2016.

[13] W. E. Hart, C. D. Laird, J.-P. Watson, D. L. Woodruff, G. A. Hackebeil, B. L. Nicholson, and J. D. Siirola, *Pyomo–Optimization Modeling in Python*, vol. 67. Springer Science & Business Media, second ed., 2017.