Evaluating the Risk of Enabling Energy Storage Systems to Provide Multiple Services

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***Abstract*—Battery energy storage systems (BESS) are emerging as a promising, versatile technology for modern power grids due to their inherent distributed nature, their ability to provide bidirectional injections and multiple grid services. With the proliferation of intermittent renewable energy resources, the BESS procurement is also expected to increase, thereby creating systematic and strategic opportunities for BESS to leverage revenue streams by providing multiple services. However, many of these services involve uncertainties which when not considered may lead to failures in service-provision. This work presents a risk-aware control strategy that takes into account the uncertainties around some of the stochastic services and ensures the BESS to deliver their service commitments. Utilizing a co-simulation architecture, this work also presents an evaluation framework to determine the true potential of utility-scale BESS for simultaneous provision of multiple services. The proposed framework is implemented for BESS installed in a real-world feeder and their performance trade-offs on multi-service provision are quantified. This promotes overall grid reliability and encourages BESS implementation through revenue stacking from providing multiple grid services.**

***Index Terms*—Battery energy storage systems, multi-service, optimization, regulation, uncertainty**

I. Introduction

With the proliferation of intermittent renewable resources, there is an increasing need for grid flexibility and smart controls to maintain reliability and safe operations. Under such requirements, there has been a renewed interest in battery energy storage systems (BESS) due to their inherent capability of providing a wide variety of grid services, like buffering variable renewable generation (e.g. wind and solar) [1], shifting peak demand, and increasing grid reliability. According to [2], the U.S. had a 4.6 GW of operational utility-scale energy storage capacity at the end of 2021, which is a 20-fold increase from 2016 (221 MW). This increased adoption of energy storage due to favorable policies and falling installation costs has led the industry to seek mechanisms to better quantify its value and increase revenue by providing various services. However, BESS when considered for just a specific service, can be under-utilized and often cost more as compared to conventional resources [3]. Existing studies have shown that using BESS to simultaneously provide multiple grid services can amplify grid benefits and increase stakeholder profitability through efficient utilization [4].

Several works in the existing technical literature have presented operational strategies and revenue potentials of BESS advocating multi-service provision [5]–[10]. The studies focus on operational strategies to enable BESS to provide mainly two categories of grid services, energy arbitrage and ancillary services (like regulation, reserves), that are directly linked with revenues along with other local objectives (e.g., congestion & voltage management). Stacking such services requires coordination between the available energy and power capacity of the BESS based on the application requirements. Towards achieving such coordination, the authors in [5], [6] have proposed deterministic scheduling approaches for BESS to participate in arbitrage and regulation markets. However, the scheduling of BESS involves uncertainties which when not considered would lead to overestimation of their true service potential. These uncertainties can be from the price predictions for the revenue-driven scheduling problem and from the actual deployment vs capacity reserved in regulation markets.

In order to address the uncertainties with prices, existing works have adopted scenario-based [9] and interval based methods, like robust optimization [10]. However, the regulation reserves are deployed based on regulation signals which are bidirectional in nature (Up/ Down) and tend to be driven randomly. Thereby, ignoring the uncertainty of regulation deployment in the planning stage may result in a coordination gap between the BESS's available energy and the instantaneous system requirements leading to failures in service-provision [6]. As the regulation service is governed by capacity commitments, failure in signal following can not only result in payment reduction but also disqualification of service [11]. Although the regulatory initiatives are driving utilities to consider the inclusion of BESSs into their asset portfolio, there exists a gap in quantifying the true potential of BESS for multi-service provision [12].

This paper presents a risk-aware modelling approach that incorporates the uncertainties of service deployments while planning BESS operations for providing multiple services. The proposed approach is implemented using a co-simulation framework that enables evaluating the BESS performance using synthetic regulation signals. The framework is implemented for BESS installed in a real-world distribution system and the trade-offs between the service delivery and monetary benefits of the BESS are quantified based on appropriate performance-based metrics and settlements designs.

II. Problem Formulation

The BESS operational strategies for providing multiple services requires coordination between their available energy and

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power capacity. This section presents the scheduling approach that models the energy limitation of the BESS coupled with its inter-temporal constraints and deployment uncertainties of the services. The grid services along with their existing market designs, considered in this approach, are discussed here:

a) Energy Arbitrage: BESS have the ability to achieve monetary benefits through energy arbitrage (EA) by charging during low prices and discharging during high prices. The economic rewards for such arbitrage are realized through the price differential between buying and selling electrical energy minus the cost of losses. BESSs, in general, are eligible to participate in day-ahead (DA) markets for energy through financially binding commitments.

b) Frequency Regulation: Although BESS are eligible to provide a variety of ancillary services (AS) in most markets, frequency regulation is a key potential source of revenue. Research and operational experience indicate that BESS's capability to provide fast and accurate response can also reduce the system's overall need for regulation [13]. Regulation up (RegUp) and down (RegDown), sometimes combined into a single regulation product, are designed to maintain tight tolerances on the system frequency. Depending on the market, a balancing authority or vertically-integrated utility procures enough regulation capacity in the DA market for regulation. During deployment, the resources are constantly dithered on a second by second basis based on instantaneous requirements. Current practice is to reimburse service providers based mainly on their reserved capacity along with a compensation for dispatch. In addition, performance-based payments have been implemented in some markets following the Federal Energy Regulatory Commission (FERC) Order 755 [14]. However, failure in providing the regulations requirements can result in payment reduction or even disqualification of service [11]. Therefore, it is important to consider the uncertainly of regulation deployment and ensure sufficient available energy for BESS to meet the system requirements when dispatched.

A. Look Ahead Problem Formulation

The BESS scheduling problem is formulated as an optimization for maximizing the profit with respect to participation in DA energy market as well as the RegUp and RegDown markets, enabling the BESS to provide multi-services. The objective function is given in (1a), where λ_t is the energy price at hour t, p_t is the scheduled exchange between the BESS and the grid during hour t, β_t^+, β_t^- are the RegUp and RegDown prices respectively, and r_t^+, r_t^- are the RegUp and RegDown capacity reserved for hour t, respectively. Bounds of the BESS power exchanges with grid are considered in (1b) and (1c) with p_t^+, p_t^- being the power injection/withdrawal into/from grid respectively and p_{max}^+, p_{max}^- being the inverter capacity limits. The constraint (1d) prevents simultaneous charging and discharging in the mathematical model. However, (1d) becomes redundant when the charging and discharging efficiencies (η^- & η^+) of the BESS are strictly less than 1 and λ_t is positive [6]. In addition to expressing power transfer between the BESS and the grid in (1e), (1f) calculates the rate of change of energy in the BESS, with p_t^{batt} being power input to the battery at the end of hour t. Constraints (1g) and (1h) determine the available regulation up and down capacity with respect to p_t and the BESS capacity limits. The dynamics of the BESS's state-of-charge (SOC) is captured through (1i), with E_s being the energy capacity and l_t being its SOC at hour t. (1j), (1k) & (1l) enforce the BESS to operate between its safe lower and upper SOC bounds ($\underline{L_t}$ & $\overline{L_t}$) and (1m) specifies the desired SOC ($l_{desired}$) at the end of the day.

$$\underset{p_t, r_t^+, r_t^-}{\text{Max}} \sum_{t=1}^{T} [\lambda_t p_t + \beta_t^+ r_t^+ + \beta_t^- r_t^-] \tag{1a}$$

$$0 \le p_t^+ \le p_{max}^+ \qquad \forall t = 1, ..., T \tag{1b}$$

$$0 \le p_t^- \le p_{max}^- \qquad \forall t = 1, ..., T \tag{1c}$$

$$p_t^+ \times p_t^- = 0 \qquad \forall t = 1, ..., T \tag{1d}$$

$$p_t = p_t^+ - p_t^- \qquad \forall t = 1, ..., T \tag{1e}$$

$$p_t^{batt} = \frac{p_t^+}{\eta^+} - p_t^- \eta^- \qquad \forall t = 1, ..., T \tag{1f}$$

$$r_t^+ \le p_{max}^+ - p_t \qquad \forall t = 1, ..., T \tag{1g}$$

$$r_t^- \le p_t + p_{max}^- \qquad \forall t = 1, ..., T \tag{1h}$$

$$l_t = l_{t-1} - \frac{1}{E_s} p_t^{batt} \qquad \forall t = 1, ..., T \tag{1i}$$

$$\underline{L_t} \le l_t \le \overline{L_t} \qquad \forall t = 1, ..., T \tag{1j}$$

$$\underline{L_t} \le l_t - \frac{r_t^+}{\eta^+ E_s} \le \overline{L_t} \quad \forall t = 1, ..., T \tag{1k}$$

$$\underline{L_t} \le l_t + \frac{\eta^- r_t^-}{E_s} \le \overline{L_t} \quad \forall t = 1, ..., T \tag{1l}$$

$$l_{desired} \le l_T \tag{1m}$$

Although the formulation models the instantaneous regulation capacities (r_t^+, r_t^-), (1i) - (il) ensures the BESS energy availability only for the scheduled dispatches (p_t^{batt}) and doesn't consider the SOC during regulation deployment. This would result in over-estimating the BESS capacity, which might lead to failures in providing the committed service.

B. Incorporating the Uncertainties in Regulation

In order to incorporate the uncertainties with regulation requirement, two uncertainty factors (τ^+, τ^-) are introduced that estimates the depth of deployments for RegUp & RegDown services respectively. The BESS energy availability is modeled using (2a)-(2d) to incorporate the deployment uncertainties. τ^+ & τ^- can be varied to control the market risks. For example, τ^+, τ^-*=1* is the safest as it ensures BESS availability for full RegUp & RegDown deployments, and τ^+, τ^-*=0* represents the riskiest case, as (2a)-(2c) simplifies to (1i), ensuring availability only for the scheduled dispatches.

$$l_t^+ = l_{t-1}^+ - \frac{1}{E_s} P_t^{batt} - \tau^+ \frac{r_t^+}{\eta^+ E_s} \tag{2a}$$

$$l_t^- = l_{t-1}^- - \frac{1}{E_s} P_t^{batt} + \tau^- \frac{\eta^- r_t^-}{E_s} \tag{2b}$$

$$l_t^\pm = l_{t-1}^\pm - \frac{1}{E_s} P_t^{batt} - \tau^+ \frac{r_t^+}{\eta^+ E_s} + \tau^- \frac{\eta^- r_t^-}{E_s} \tag{2c}$$

$$\underline{L_t} \le l_t^+, l_t^-, l_t^\pm \le \overline{L_t} \qquad \forall t = 1, ..., T \tag{2d}$$

where l_t^+, l_t^- and $l_t^\pm$ are the BESS SOC considering only RegUp , RegDown and both RegUP & RegDown deployments.

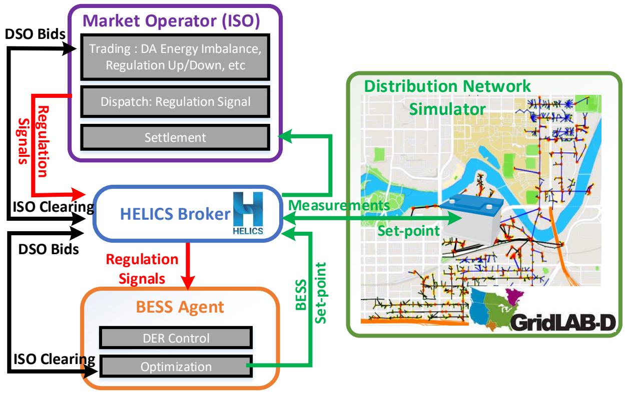

Fig. 1. Co-simulation Framework for performance evaluation.

III. Co-Simulation Framework

The proposed operational strategy is implemented using a co-simulation framework (shown in Fig. 1) to facilitate performance evaluation. The different layers of the framework are discussed here:

a) BESS-Agent: The BESS agent determines the DA operational schedule and regulation reserves based on the foretasted prices (of energy & regulation) and pre-decided risk factors (τ^+, τ^-) which are communicated to the market operator. During operation, the regulation requirements are deployed along with the operation schedule. The agent is implemented as a Python script.

b) System Operator: The system operator is implemented as a self-contained agent in Python which facilitates emulating the market processes for providing grid services.

Trading: For the simplicity of implementation, the BESS are considered to be price takers and thereby all schedules and reserves commitments are granted.

Service deployment: The system operator procures the required regulation reserves in the DAM. During operation, the reserves are deployed based on the instantaneous system needs. The resources are dispatched based on their commitments through regulation signals which depend on the system-wide energy exchanges and are extremely difficult to model. This work leverages the SynAS module [15] to generate regulation signals. The module provides synthetic AS signals based on 6 months of real regulation signals for a stationary battery participating in CAISO's AS market. The regulation signals are scaled based on the reserved capacity and are send to the BESS-Agent every 4-seconds for dispatch. Incorporation of the SynAS module facilitates a realistic simulation environment to evaluate the BESS performance.

Settlement: The settlement design for BESSs providing multiple services is given by (3). The DA revenues (C_{net}^{DA}) are computed for individual services based on the market clearing price (MCP). However, the capacity-based compensation for reserves are subject to performance and failure in providing the services are reflected through penalties. This facilitates estimating the true revenue of BESS along with the impacts of over-estimating the BESS's service potential.

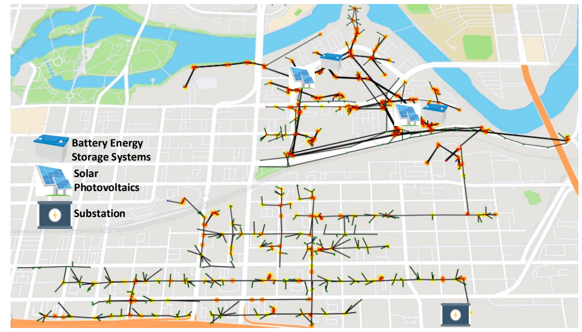

Fig. 2. Schematic of the Test system along with the BESS locations.

TABLE I
Battery Specifications

Device Name	Energy Capacity	Charge Efficiency	Discharge Efficiency	Inverter rating	SOC limits
BESS1	1506.6 kWHr	0.95	0.95	500.00 kW	[0.1, 0.9]
BESS2	334.8 kWHr	0.95	0.95	168.15 kW	[0.1, 0.9]

$$C_{net}^{DA} = \sum_{t=1}^{T} \lambda_t^{DA} * p_t + \sum_{t}^{t \in T^+} \beta_t^{+DA} * r_t^+ + \sum_{t}^{t \in T^-} \beta_t^{-DA} * r_t^- \quad (3)$$

where λ^{DA} is the DA-MCP for energy, β^{DA} is the DA-MCP for regulation reserves. and T^+ & T^- denotes the set of intervals where the BESS were able to provide their committed RegUp and RegDown services respectively.

c) Distribution System Simulator: The distribution system network is modeled using GridLAB-D™ [16] that allow users to integrate detailed models of end-use technologies and DERs. BESS operations are incorporated using GridLAB-D's battery and grid-forming inverter models. During operation, the BESS are controlled by the agent using a net dispatch signal based on their EA schedule and regulation signals.

d) Information Exchange: The proposed co-simulation architecture is implemented using the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) [17]. HELICS allows time-synchronized information exchange among simulators enabling the BESS-Agent to adjust operation of devices based on the regulation deployments.

IV. Use-case Description

The proposed framework is implemented on a real-world distribution system, located in WA, USA, and operated by Avista Corporation. Fig. 2 shows the footprint of the 13.2-kV distribution feeder. The feeder model has been derived and validated from data directly available from the utility enterprise systems. Further details of the model development and validation is presented in [18]. The utility has recently installed two BESS in the feeder (see Fig. 2), the specifications of which are given in Table I. The proposed control strategies are implemented on the BESSs to evaluate the revenue potential and the risk of enabling them for multi-service provision.

Market information including locational marginal price (LMP) for energy, RegUp, and RegDown for a nearby participating CAISO node were used as a reference for the analysis. CAISO data is a good proxy, considering the utility doesn't

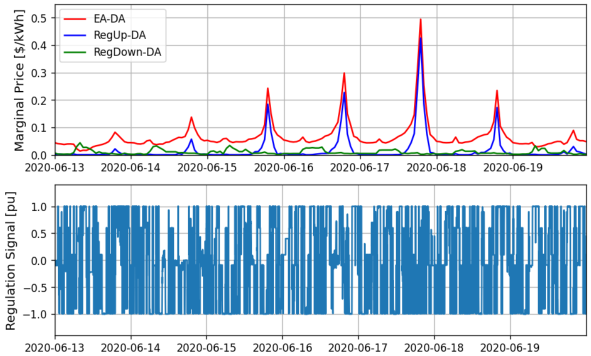

Fig. 3. CAISO cleared LMPs and regulation signal over the summer days.

TABLE II
EXPECTED REVENUE OF BESS PROVIDING EA VS MULTI-SERVICES

Service Cases	Expected Revenue
EA only	$1644.14
EA + Regulation	$2,815.35

currently participate in an organized DA market for these services. This data was collected from the ISO's open access same-time information system (OASIS) [19]. The regulation deployment signals were generated from the SynAS module which is also based on CAISO (as discussed in Sec. III).

V. EVALUATION & RESULTS

The proposed use-case is evaluated over a selected summer week in 2021. Fig. 3 shows the EA, RegUp, and RegDown LMP for the selected days along the regulation dispatch signal obtained from the SynAS module.

A. EA vs Multi-Service

In order to estimate the BESS revenue potential for multi-service provision, the scheduling approach proposed in Sec. II is evaluated with an EA only case. Table II shows the expected revenues for the two cases when implemented without considering deployment uncertainties. The results clearly indicate that enabling the BESSs to provide multiple-services enhances the utility's expected revenue (by $\sim 70\%$) as compared to EA which is consistent with existing literature [5], [6]. However, incorporating the uncertainty of regulation deployments would constrain the BESS capacity for providing multiple services and thereby also impact their revenue stacking potential.

B. Risk of Multi-Service Provision

In order to quantity the risk of multi-service provision, the proposed approach is evaluated for a range of uncertainty factors as given below:

- τ^+= **0**, τ^-= **0** (**High-risk**): Doesn't ensure BESS availability for both RegUp & RegDown commitments.
- τ^+= **1**, τ^-= **0**: Ensures BESS availability only for the full range of committed RegUp deployments.
- τ^+= **0**, τ^-= **1**: Ensures BESS availability only for the full range of committed RegDown deployments.
- τ^+= **0.5**, τ^-= **0.5**: Ensures BESS availability for a 50% depth of RegUp & RegDown deployments.

TABLE III
BATTERY PERFORMANCE OVER A RANGE OF UNCERTAINTY FACTORS

τ^+	τ^-	Service Provision	Safe Limits	DA Revenue Expected	Revenue DA Actual	BESS Cycles BESS1	BESS Cycles BESS2
0	0	78.9%	73.1%	1,837.5$	$1,313.0	6.2	7.1
1	0	91.2%	38.2%	1,294.4$	$1,248.4	2.1	2.9
0	1	93.2%	44.7%	1,393.1$	$1,370.2	2.7	3.0
0.5	0.5	100%	97.2%	1,133.0$	$1,133.0	3.5	4.1
1	1	100%	100%	947.4$	$947.4	3.9	4.9

TABLE IV
BATTERY PERFORMANCE OVER THE SUMMER WEEK

τ^+	τ^-	Service Provision	Safe Limits	DA Revenue Expect.	Revenue DA Actual	BESS Cycles BESS1	BESS Cycles BESS2
0	0	77.6%	71.8%	$2,815.35	$2471.74	15.19	17.64
1	1	100%	100%	$1,226.81	$1,226.81	8.89	10.43

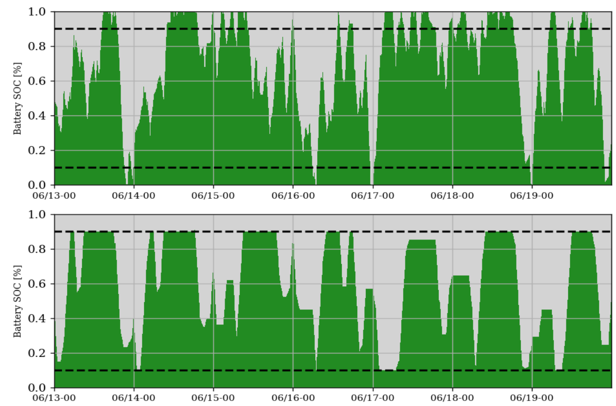

Fig. 4. SOC of the BESS1 for the *High-risk* (top) & *No-risk* (bottom) cases.

- τ^+= **1**, τ^-= **1** (**No-risk**): Ensures BESS availability for the full range of RegUp & RegDown commitments.

Each of the cases are simulated over a three day period (16th - 19th June), with regulation deployments from SynAS and both BESSs starting at 50% SOC. Table III compares the BESS performance over different levels of uncertainty during multi-service provision. Results indicate that for lower values of τ^+ & τ^-, the expected revenue estimates (*DA Expect.*) are (upto $\sim 40\%$) higher than the actual compensation (*DA Actual*). This is mainly due to payment penalties as the BESS failed to provide their committed service during several intervals when lower deployment uncertainties were considered. This is also presented in Table III as service provision which indicates the % of time the BESS were able to provide their committed services. Although the *High-risk* case (τ^+= **0**, τ^- = **0**) produced $364 ($\sim 38\%$) more in actual revenue over the three day period than the *No-risk* case, the BESS were only able to provide their committed grid services 78.9% of the time due to over-estimates of energy availability. The failure in providing the services will not only result in payment reduction but may also lead to disqualification of service by the operator. However, for the τ^+,τ^-= **0.5** case, the BESS were able to generate 20% more revenue than the *No-risk* case while maintaining a 100% servicing provision. This shows that BESS can leverage extra revenues if the deployment uncertainties can be appropriately estimated.

Table IV presents the results of a week-long simulation for the two extreme cases (*High-risk* & *No-risk*). The BESS were

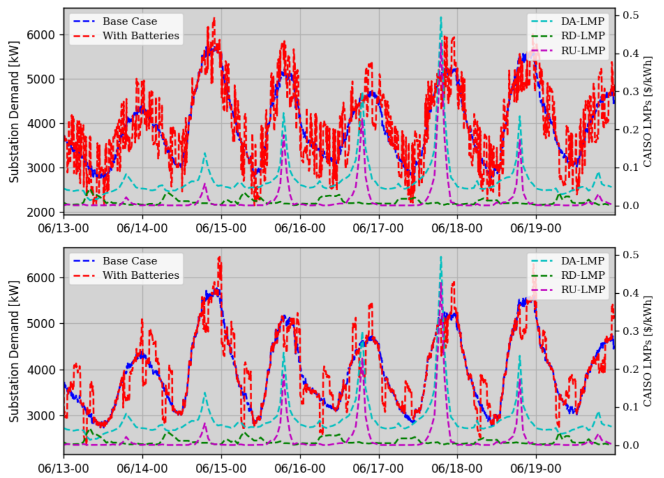

Fig. 5. Net feeder demand for the *High-risk* (top) & *No-risk* (bottom) cases.

able to provide their committed services during deployment and keep their SOC within the safe operational limits for the *No-risk* case (see Fig. 4). The *High-risk* case overestimates the service potential of BESS as it doesn't consider the energy availability due to possible deployments. This leads to BESS unavailability during some of the deployment intervals, as shown in Fig. 4, leading the devices to provide low service accuracy ($\sim$77%) and operate beyond their safe limits over longer durations ($\sim$72% of the time). Also, the BESS operate at more than 2 cycles per day for the *High-risk*. This may degrade the BESS-life by more than 50%. Whereas, for the *No-risk* case, the BESS operates at approximately 1 cycle per day which is close to the manufacturer recommendation.

The impact of BESS participation on the net feeder demand, metered at the substation, for the two cases, is shown in Fig. 5. It can be seen that the heavy commitments in the *High-risk* case would cause frequent deployments leading to a very high volatility in the feeder demand. This might also lead to voltage fluctuations and frequent tap-changing requirements.

VI. Conclusions

This work presents a risk-aware modeling approach that incorporates the uncertainties of service deployments while enabling BESS to provide multiple services. The approach is complimented with a co-simulation framework for testing and evaluating the true service potential of the BESS. The proposed approach enables the BESS to provide their committed services by responding to the service deployments at all times and thereby guarantees service provision to the system operator. Results also indicate that the deployment uncertainties, when not considered, would over-estimate the BESS's potential, leading to failures in service-provision. Ensuring the quality of service is key step towards enabling BESS for providing multiple services and thereby enhancing their revenue-stacking potential.

Future extension of this work would aim towards including network constraints like voltage limits, and substation limits in the formulation. Another direction of future work would be towards investigating the BESS potential for short time service provision (for e.g., 15-minute regulation markets) by utilizing any available BESS energy due to under-deployed reserves.

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