



Detailed Project Report

Pilot Project : AGC-Enabled 5MW / 2.5 MWh Battery Energy Storage System



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About GETRI



Green Energy Transition Research Institute (GETRI), erstwhile Gujarat Energy Training and Research Institute (GETRI), an ISO 9001: 2015, CEA accredited and DUNS registered Institution, located at Vadodara, Gujarat, is an autonomous institute promoted by Gujarat Urja Vikas Nigam Limited (GUVNL) and its group companies and is registered under Bombay Public Trust Act. It was founded in 2006 with the core mission of fostering continuous employee development through comprehensive training and research programs. These programs are designed to keep participants updated on the latest developments in the ever-evolving energy sector and help them implement best practices in their work. In addition to its role as a training and capacity-building organization, GETRI also holds a crucial mandate as a think tank. It serves as a knowledge hub and advisory body for both the government of Gujarat and the power sector. This role involves providing valuable insights, conducting research, and offering recommendations on policy matters, industry trends, and sustainable energy practices. GETRI further extends its influence by taking up consultancy projects. These projects involve collaborating with government bodies, power sector organizations, and other stakeholders to provide expert guidance and solutions for various energy-related challenges and initiatives. With its extensive expertise and resources, GETRI contributes significantly to the overall growth and development of the energy sector in Gujarat and beyond.

CNET: Center for Net-zero Energy Transition



As the energy landscape continues to evolve rapidly, the need for innovative solutions and expert guidance in the quest for sustainability becomes increasingly vital. With a resolute commitment to power Gujarat state's progress and sustainability, GUVNL established the Centre for Net Zero Energy Transition (C-NET) at GETRI, Vadodara, in 2022. C-NET stands as a testament to GUVNL's dedication to innovation and thought leadership. Functioning as a dynamic think tank, this cell is strategically focused on addressing the challenges and opportunities associated with decarbonization and net-zero goals. The vertical of GETRI serves as a catalyst for generating cutting-edge ideas, strategies, and solutions to steer the energy sector towards a low-carbon future. This visionary move of creating C-NET signifies an acknowledgement of power utilities' role in driving the transformation towards a sustainable energy future. C-NET serves as a knowledge hub, generating innovative ideas, strategies, and solutions that accelerate the energy sector's transition to net-zero emissions.

Executive Summary

As Gujarat advances toward its ambitious 100 GW renewable energy target by 2030, the resulting intermittency has placed unprecedented stress on the state's grid control area. This Detailed Project Report (DPR) proposes the implementation of **AGC-enabled 5 MW / 2.5 MWh Battery Energy Storage System (BESS)** as a strategic imperative for grid security and stability. Unlike traditional energy-storage deployments in India, this project intends to deploy a high-power 2C rating BESS, specifically optimized to provide Secondary Reserve Ancillary Services (SRAS) through a sub-second response to minimize Area Control Error (ACE) of Gujarat State.

This Pilot is uniquely positioned as a specialized **Regulatory Sandbox**, funded entirely through a dedicated financial grant from the Government of Gujarat (GoG). In this pilot, the BESS is envisaged to function as a transmission element. Consequently, charging energy will be drawn directly from the grid, with all associated operational and round-trip efficiency (RTE) losses integrated into the state's transmission loss framework and socialised across grid users. By connecting at the 66 kV State Transmission Utility (GETCO) boundary, the pilot envisages a modular architecture featuring Lithium Iron Phosphate (LFP) technology and a high-speed AGC command loop using the IEC 60870-5-104 protocol.

Commercially, the pilot is structured under a "Storage as a Service" (StaaS) model, with an estimated total outlay of **₹ 510 lakhs over a 2-year period**. This includes a budgetary fixed service fee of ₹ 4.0 lakhs per MW per month and a one-time Project Management Consultancy charge.

While the socialization of operational losses represents a collective cost, the commercial impact remains profoundly positive for the system. By utilizing a benchmark rate of ₹ 4.70 per unit (the weighted average DSM rate for the region), simulation analysis based on a full year of WRPC deviation data (2025) confirms that the BESS effectively "clips" high-cost deviation peaks during critical grid conditions. Consequently, the pilot is set to be a cost-saving project, **estimated to provide annual net savings to grid users of ~₹70 Lakhs**. Ultimately, this GoG-funded initiative intended to serve as a blueprint for the modernization of the state's power sector, proving that when BESS is integrated as a transmission-level stability tool, it not only helps securing grid but also yields financial gains that far outweigh the socialised costs of its operation.

1.0 Introduction and Context

Gujarat is at the forefront of India's energy transition, characterized by an aggressive expansion of renewable energy (RE) resources. The State Government has set a visionary target to achieve 100 GW of Renewable Energy capacity by 2030. This ambition is anchored by the "Mission 100 GW," launched during RE-INVEST 2024, which aims to position Gujarat as a global hub for green energy and to contribute significantly to India's national goal of 500 GW of non-fossil fuel capacity.

As of December 31, 2025, Gujarat has already integrated a formidable RE portfolio. According to the state's system operator records and official government data, the cumulative installed RE capacity in the state has reached approximately 42.58 GW, making it the leading state in India for renewable contributions. This capacity includes:

- Solar Power: ~25,529 MW (including rooftop solar installations).
- Wind Power: ~14,821 MW (ranking first nationally).
- Others: Including Wind-Solar Hybrid projects (~2,399 MW) and Biomass/Small Hydro.

While this growth is a major milestone, the increasing share of intermittent RE—without a commensurate increase in flexible storage or balancing mechanisms—poses a severe risk to the grid's stability and security. The variable nature of wind and solar generation creates rapid imbalances between demand and supply.

In the absence of fast-responding reserves like BESS, the system operator is often forced to curtail renewable energy to maintain grid parameters. This curtailment results in:

1. Direct Revenue Loss: Financial setbacks for RE developers who lose out on generation payments.
2. National Loss: Wasted green energy that could have displaced fossil fuel generation, hindering carbon reduction targets and economic efficiency.

To mitigate these risks and support the 100 GW roadmap, the deployment of fast-acting, AGC-enabled storage assets is no longer optional but a strategic necessity for the state grid.

2.0 Government Grant for Energy Transition-related Pilots

To tackle the challenges of the Energy Transition, the Government of Gujarat (GoG), recognising the critical need for smart grid management, has provided financial support for conducting pilots. Vide resolution no. EPCD/WOB/efile/20/2024/2289/K Dated 7th April-2025, the GoG has conveyed administrative approval for a financial assistance grant of ₹ 25 Crores to the CNET, GETRI for the Financial Year 2025-26 to support energy transition activities, including an allocation of Rs 5 crores for this Pilot project.

3.0 Operational Assessment, Reserve Requirements, and Regulatory Landscape

3.1 The Need for Fast-Response Reserves

Currently, the state's system operator (SLDC) does not have a fully functional Automatic Generation Control (AGC) system for its intra-state generating stations. The grid operator relies primarily on manual methods to balance real-time fluctuations. When a frequency deviation or ACE spike occurs, the operator must issue verbal or manual instructions to conventional generators to ramp their generation up or down.

This manual method of grid control faces several critical limitations:

- **Inefficiency and Delay:** The human-in-the-loop process introduces significant latency between identifying a deviation and the actual change in plant output. This delay often results in substantial deviations at the state periphery, leading to higher financial penalties under the current Deviation Settlement Mechanism (DSM).
- **Technological Constraints of Thermal Fleet:** The state's primary balancing relies on a conventional thermal fleet. Many of these units are aged and have inherent technical limitations, with typical ramp rates of 1% to 3% per minute. Such slow response times are fundamentally mismatched with the rapid, second-to-second variability of a 40 GW+ renewable portfolio.
- **Lack of Hydro resources:** Unlike some other Indian states, Gujarat does not have sufficient flexible hydro-generation capacity that could typically provide rapid "peaking" or frequency support. This absence of high-ramp hydro assets makes real-time grid management exceptionally challenging for the system operator.

In this context, an AGC-enabled BESS offers a "surgical" solution, providing sub-second response times that can bridge the gap left by manual processes and slow-moving thermal units, thereby ensuring grid security and stability.

3.2 Analysis of Area Control Error (ACE) and deviations for the Gujarat State

A detailed analysis of the state periphery for the year 2025 reveals significant technical challenges in real-time grid balancing and ACE management, primarily due to the lack of fast-acting active reserves. The following data highlights the performance gap that this pilot BESS project aims to address:

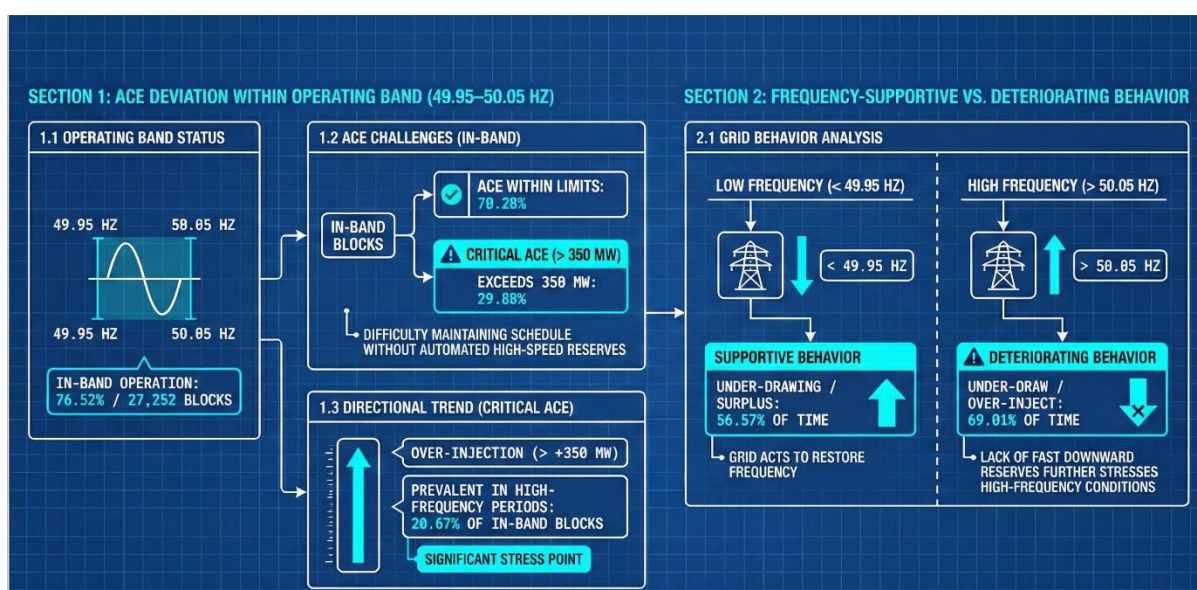


Figure 1: Analysis of Deviations and Area Control Error (ACEs) at Gujarat State's Boundary. (2025)

1. ACE Deviation within the Operating Band (49.95–50.05 Hz):

The grid operates within the "allowable band" for most of the time (27,252 blocks, or 76.52%). However, even within this stable frequency range, the state faces challenges in maintaining its Area Control Error (ACE).

- In nearly 30% of the "in-band" blocks, the ACE exceeds 350 MW, highlighting the difficulty of maintaining schedule adherence without automated high-speed reserves.
- Directional Trend: Over-injection during high-frequency periods is more prevalent, with ACE exceeding +350 MW in 20.67% of in-band blocks.

2. Frequency-Supportive vs. Deteriorating Grid Behaviour

A key technical challenge identified is the difficulty in providing adequate frequency support, especially during over-frequency events in the absence of real-time fast reserves:

- During Low Frequency (< 49.95 Hz): The grid behaviour is supportive (under-drawing/surplus) 56.57% of the time.
- During High Frequency (> 50.05 Hz): The grid behaviour is deteriorating 69.01% of the time. Without fast-responding downward reserves, the state tends to under-drawal or over-injection, inadvertently placing further stress on high-frequency conditions.

This trend indicates that, as variable RE penetration increases, the state faces surplus generation issues for a significant portion of the time. This behaviour highlights a serious deficit in "Down Reserve" capacity, which often necessitates RE curtailment as the primary tool for grid balancing, leading to green energy waste.

The analysis underscores a persistent technical challenge during high-frequency events, where deviations are in the deteriorating direction ~69% of the time. The 5 MW BESS pilot is strategically designed to provide the necessary real-time fast active reserve, acting as a precision tool to absorb surplus power through AGC Down commands instantly, provide critical downward regulation, and inject power through up commands during times of low frequency, thereby minimizing the ACE.

3.3 Secondary Reserve Requirements (FY 2025-27)

Grid India (National Load Despatch Centre) has formally notified the reserve requirements for the Gujarat Control area, emphasizing the need for robust Secondary Reserve Ancillary Services (SRAS) to ensure grid reliability. The specific reserve requirements are summarized in the table below:

Table 1: Reserves to be maintained by Gujarat State (As notified by Grid India)

Financial Year	Reserve Type	Within State (MW)	At ISGS Level (MW)	Total SRAS Required (MW)
FY 2025-26	SRAS Up	558	286	844
	SRAS Down	436	853	1289
FY 2026-27	SRAS Up	402	745	1147
	SRAS Down	409	758	1167

Despite these notifications at the national level, the mandated reserves are not consistently available within the state system. This availability gap is primarily due to a lack of coordinated planning at the state level, which makes it difficult for the system operator to effectively call on and deploy these reserves to manage real-time imbalances. The 5 MW pilot serves as a much-needed "contingency reserve" to address this challenge by establishing a dedicated, automated infrastructure to reliably meet a portion of this requirement.

3.4 Regulatory Gap

There exists a prominent gap in the current state-level regulatory framework concerning the procurement and dispatch of ancillary services. While the Central Electricity Regulatory Commission (CERC) has established a robust mechanism for Secondary Reserve Ancillary Services (SRAS) at the interstate level, a corresponding intra-state framework is largely absent in Gujarat.

Key regulatory challenges include:

- **Lack of Real-Time Procurement Mechanism:** Under the existing framework, the system operator cannot procure ancillary services in real-time from third-party storage or flexible assets if the mandated reserves are not maintained by the grid users.
- **Absence of Compensation Framework:** There is no defined tariff or commercial settlement process for intra-state BESS assets providing frequency regulation, making it difficult for private developers to participate under a market-based model.
- **Coordination Gaps:** The disconnect between national-level reserve notifications (by Grid India) and state-level resource planning creates a vacuum where reserves exist on paper but cannot be utilized to mitigate ACE deviations in real-time.

This pilot project aims to bridge this gap by demonstrating a *regulatory sandbox* providing the empirical data necessary for the state regulator to formulate a comprehensive state-level Ancillary Services regulation.

4.0 Project Scope & Technical Aspects

4.1 About the Project

This pilot project involves the installation, commissioning, and operation of a **5 MW / 2.5 MWh** (2C-rate) standalone Battery Energy Storage System (BESS) dedicated to grid support functions. The project is designed to serve as a **fast-response resource for Secondary Reserve Ancillary Services (SRAS)**, enabling the system operator to manage real-time imbalances with high precision. By utilizing Automatic Generation Control (AGC) over 4-second intervals, the project aims to demonstrate the technical viability of BESS in reducing Area Control Error (ACE) by controlling unintended deviations in a high-renewable penetration scenario. While not the primary objective, the project may also explore the deployment of BESS to provide Primary Reserve Ancillary Service (PRAS) up to 5% of the rated capacity to evaluate its effectiveness in primary frequency response.

4.2 Business Model: Storage as a Service (StaaS)

The project will follow a *Storage-as-a-Service (StaaS) model*, in which the Developer (Service Provider) is responsible for capital investment, installation, commissioning, and comprehensive O&M of the BESS asset for maximum 2-3 years. The order-placing agency will pay a fixed monthly service fee (₹/MW/Month) based on the system's "Availability".

Rationale for the StaaS Model in a Pilot Context:

1. **Unsuitability of BOOT/CapEx:** Traditional Build-Own-Operate-Transfer (BOOT) or CapEx models typically require long-term commitments (10-12 years) to amortize the high initial capital expenditure of BESS technology. Given that this is a "Regulatory Sandbox" pilot intended to validate performance and refine state-level regulations, committing to long-term ownership or large upfront CapEx is not strategically viable.
2. **Tenure Flexibility:** The project duration is specifically envisaged for an **initial 2 years, which may be extended by 1 year** based on the observed benefits and fund availability. The StaaS model allows the utility to "rent" the capability without being burdened by a stranded asset if technology or regulations shift after the pilot phase.
3. **Risk Mitigation:** BESS technology for AGC applications involves aggressive 2C cycling, which poses high risks regarding battery degradation and thermal management. Under the StaaS model, all technical, operational, and replacement

risks are transferred to the Developer, who is best positioned to handle them with the required professional expertise.

4.3 System Configuration Options

The project is envisaged to be connected to 66 kV at the 66 kV Gotri B Substation, Vadodara, within the same campus where the State Load Distribution Centre, Gujarat, functions. The State Transmission Utility will provide the required space. Two physical configuration options are proposed for the 5 MW / 2.5 MWh system to ensure operational reliability.

Option 1 (Modular Configuration): This option utilizes a 2 x 2.5 MW / 1.25 MWh setup. This is the technically optimal design for the pilot, utilizing two independent blocks. Each block consists of an independent Battery Container, a Power Conversion System (PCS), and an Inverter Duty Transformer (IDT).

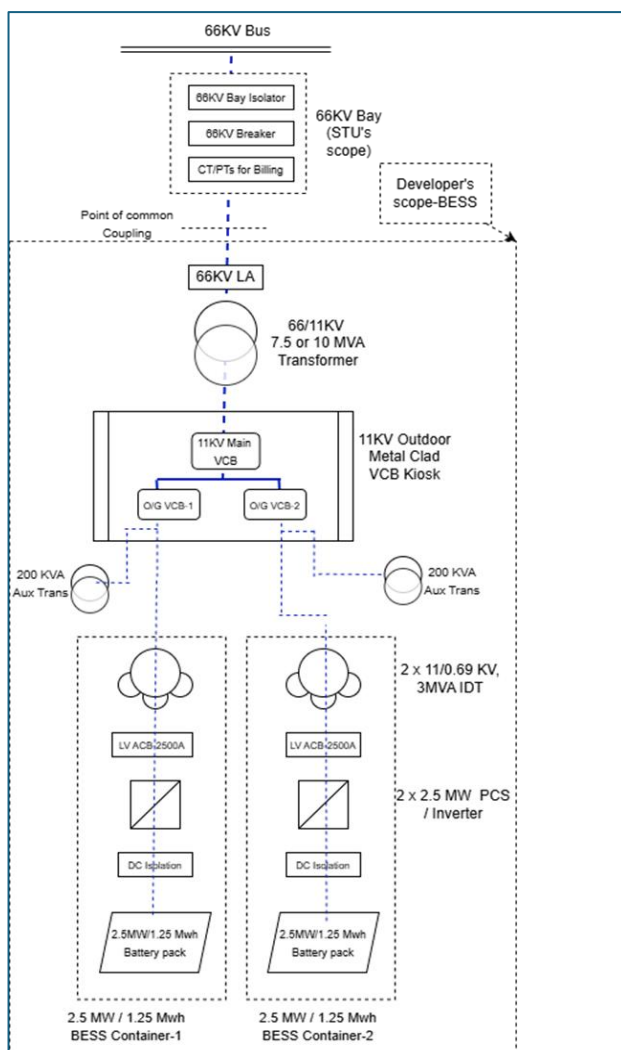


Figure 2: Single Line Diagram- Modular configuration.

Pros & Cons of Option-1:

1.Pros: Optimized Cable sizing

For a 5 MW system, the aggregate current at the Low Voltage (LV) AC side (standard inverter output of 0.69 kV) exceeds 4,200 Amperes. Terminating such a high current magnitude requires upwards of 12 to 14 runs of 400 sq mm cabling, posing significant thermal management challenges, resistive losses (I^2R), and practical termination logistics at the transformer/PCS bushings. By adopting a modular 2.5 MW configuration, the LV current per block is reduced to approximately 2,100 Amperes, well within industry-standard practices for cabling and termination kits.

2.Pros: Redundancy

This configuration provides high system availability. In the event of a technical fault or scheduled maintenance on a container/PCS, the system can continue to provide 50% (2.5 MW) of the contracted capacity to the grid.

3. Pros: Market Availability of Inverter Duty Transformers (IDT):

The BESS is envisaged to connect to the 66 kV grid; a 66/0.69 kV IDT is a non-standard and custom-built item that lacks the high-impedance characteristics required for inverter harmonics. The optimal market strategy is to use standard 11/0.69 kV or 33/0.69 kV IDTs for the first stage of step-up, followed by a standard 11/66 kV Power Transformer at the substation yard.

4. Cons: Space requirement

Estimated footprint for a modular 2.5 MW setup, including clearances, is approx. 350 - 400 sq. meters (including switchgear and auxiliary systems).

Option 2 (Integrated Configuration)

This option envisages a single integrated container. While more footprint-efficient, it

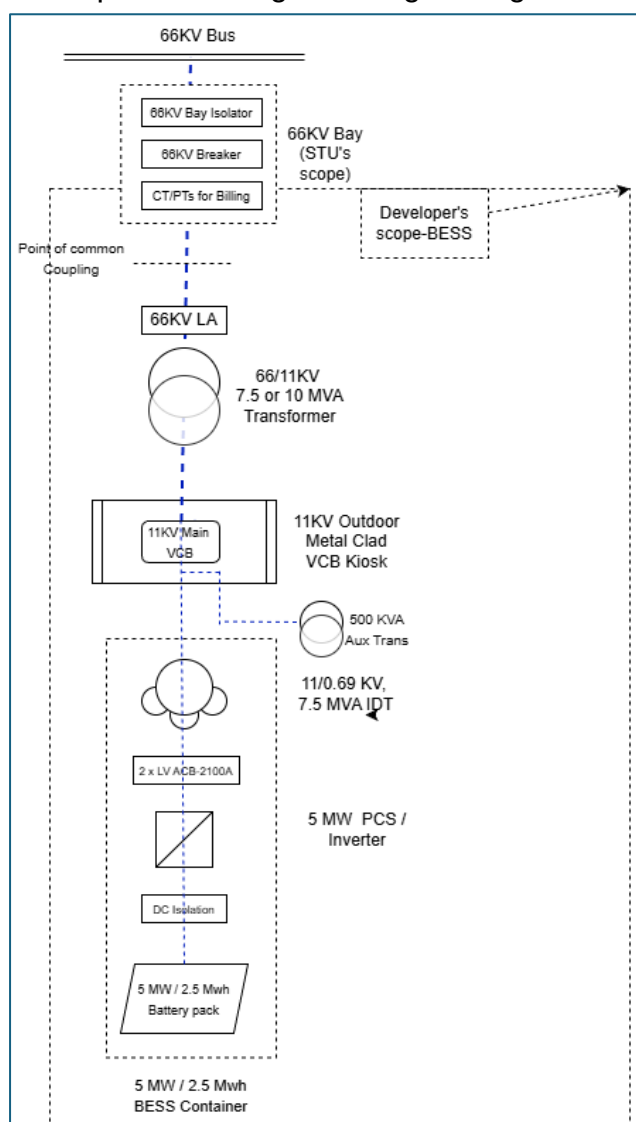


Figure 3: Single Line Diagram: Integrated configuration

faces the technical deterrents of excessive LV side currents and thermal density. While being more land-footprint-efficient, it faces the technical deterrents of excessive LV side currents and thermal density. However, some of these can be mitigated through strategic approaches, as discussed below.

Dual Secondary Transformer Logic:

To address the termination of ~4.2kA, the single-block design utilizes a Dual Secondary IDT (typically 7.5 MVA, 11/0.69-0.69 kV). This allows the 5 MW inverter output to be split into two parallel LV paths (2 x 2,100A), terminated via two independent Air Circuit Breakers (ACBs).

Thermal Management Requirement:

Due to 2C cycling in a single high-density enclosure, Active Liquid Cooling is mandatory to prevent thermal runaway.

Pros: Compact Design, lesser land-footprint: This is one of the biggest merits of this configuration. Estimated

footprint for a single integrated 5 MW block is approx. 220 - 260 sq. meters, offering a saving of ~35% over the modular approach, making it suitable for congested brownfield substations.

While "All-in-One" integrated containers (where PCS is inside the battery container) are available in the market, for this pilot, the separate provision of PCS and BESS container has been envisaged in both the configurations. The rationale for the same is discussed hereunder.

Thermal Isolation: At a 2C high-power rate, both the batteries and the PCS generate maximum heat simultaneously. Physical separation prevents thermal cross-contamination, ensuring that the inverter's heat does not accelerate battery degradation.

Enhanced Ventilation & Summer Performance: In Gujarat's extreme ambient temperatures (up to 48°C), integrated units often "derate" power output due to internal heat soak. A standalone PCS kiosk allows for superior natural and forced-air ventilation, ensuring the full 5 MW capacity is always available.

O&M Serviceability: Separating the power electronics from the chemical storage environment enables safer, more rapid maintenance of the PCS without exposing the battery environment to external dust or humidity during repairs.

Table 2: Summary of approximate dimensions and space requirement

Component	Option 1 (2 x 2.5 MW)	Option 2 (1 x 5 MW)	Industry Standards (Ref)
BESS Container	2 x 20ft (6.1m x 2.4m each)	1 x 40ft (12.2m x 2.4m)	ISO Standard Containers
PCS Unit	2 x Kiosk (3.0m x 2.5m each)	1 x Kiosk (6.0m x 2.5m)	Sungrow / SMA SC Series
IDT Unit	2 x 3 MVA (2.5m x 2.2m ea)	1 x 7.5 MVA Dual Sec.	ABB / Siemens / Schneider
O&M Clearance	3m Front/Back; 2m Sides	3m Front/Back; 2m Sides	IE Rules / CEA Standards
Total Area	~375 sq. m	~245 sq. m	Total incl. 11/66kV Yard

4.4 Communication & AGC Infrastructure

In alignment with the Grid-India Consultation Paper (Dec 2025), the communication architecture for BESS is designed to meet the high-speed requirements of Secondary Reserve Ancillary Services (SRAS). The infrastructure ensures a deterministic, low-latency link between the BESS Local Controller and the system operator's SCADA/AGC system.

4.4.1 Communication Protocol

The system shall utilize IEC 60870-5-104 (TCP/IP based) as the primary protocol for real-time data exchange. Alternatively, DNP3 over secure IP may be used if required by the existing SCADA gateway. All communications must be over a secure, dedicated fiber-optic link (MPLS or Leased Line) to ensure cybersecurity and high availability.

Latency Requirements: The end-to-end signal latency, defined as the time from the generation of the AGC set-point at the SLDC to the actual change in the BESS output, must be less than **4 seconds**.

4.4.2 AGC Signal List for BESS

A signal list for integrating Battery Energy Storage Systems (BESS) under Automatic Generation Control (AGC) has been prepared by Grid India (NLDC)¹. The same is adopted in this pilot. This signal list includes specific considerations for the unique characteristics of BESS. These considerations include:

- 1. Charging and Discharging Signals:** The signal list has been designed to manage the charging and discharging processes of the BESS, ensuring that the system operates efficiently during both modes.
- 2. State of Charge (SOC) Monitoring:** Signals have been incorporated for continuous monitoring of the State of Charge (SOC) in MWh of the BESS, which is crucial for determining the energy available for discharging and the need for charging. SOC% is defined as the ratio of the available energy (in MWh) to the rated energy capacity (in MWh) of the BESS.
- 3. Sign Convention Adjustments:** The sign conventions have been suitably defined to handle the dual modes of operation (charging and discharging), which distinguishes BESS from conventional power plants that typically operate in generating mode.

AGC signal list is depicted in Figure. The same is described as under.

- 1. Maximum MW permissible:** It is the maximum MW which can be discharged (+ve value) / charged (-ve value) by the BESS at any particular point of time.
- 2. Minimum MW permissible:** It is the minimum MW which can be discharged (+ve value) / charged (-ve value) by the BESS at any particular point of time.

¹ Grid India has published a draft Paper, "Automatic Generation Control of REGS, BESS, and PSP in India, wherein section 3.5 discusses about the AGC BESS signal list

3. **Ramp rate up permissible:** It is the maximum MW/min with which the BESS can be discharged (+ve value) by AGC at any particular point of time.
4. **Ramp rate down permissible:** It is the maximum MW/min with which the BESS can be charged (-ve value) by AGC at any particular point of time.
5. **Actual MW:** It is the actual charge/discharge MW value of the BESS.
6. **Scheduled MW or ULSP:** It is the schedule of the BESS, for fulfilling the stakeholder contracted energy/power. It is analogous to Unit Load Set-Point (ULSP) or RLDC schedule of a conventional power plant. Without Ancillary Services (SRAS and TRAS), BESS would discharge/charge this MW value. This Scheduled MW (ULSP) would be positive value while discharging, and negative value while charging.

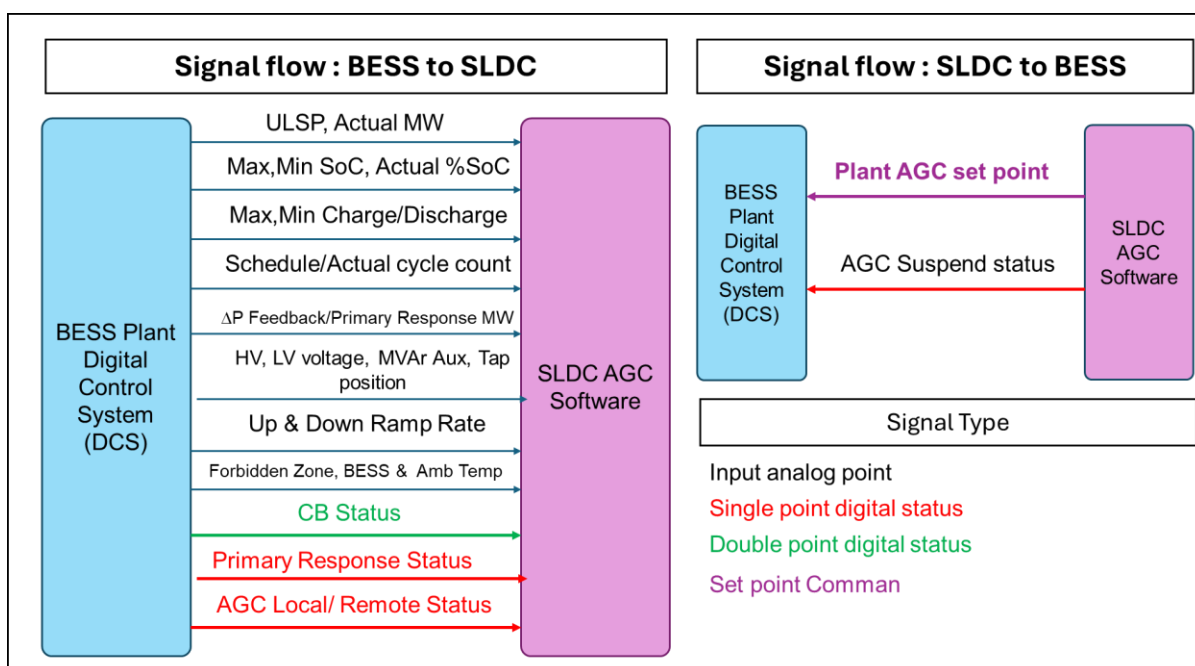


Figure 4: AGC Signal list for BESS

7. **Circuit Breaker status:** To understand whether the BESS is on or off. Ensuring the quality of this information is also very critical for AGC. This is a double point signal (2 - CB closed, 1 - CB open, 0 - in between).
8. **Local/Remote status:** The manual choice to take the BESS into local or remote is with the plant shift engineer through DCS. A suitable user interface may be developed by the instrumentation team at every plant for taking BESS into Local/Remote. This is a single-point digital signal (0 – Local, 1- Remote). “Remote” means unit Delta P may be added to ULSP before processing the signal for maximum and minimum limits and further sending it to master control. Thus, if a BESS is in Remote, it is ready to accept and respond to AGC signals. “Local” means block Delta P may not be added to ULSP. This choice can be because of onsite problems, non-readiness to accept AGC signals, prolonged communication failure, etc.

9. **Minimum State of Charge SOC % permissible:** It is the minimum value of SOC % up to which a BESS can be discharged. Default value would be 10-20%. Default Maximum SOC would be 100% (Additional signal may be configured, if needed).
10. **Actual State of Charge SOC %:** It is the current value of SOC % of the BESS. Beyond Maximum and Minimum SoC%, AGC software would stop sending AGC signals to BESS.
11. **Scheduled Cycle (0-100%) Count per day (number):** It is the number of round-trip cycles of BESS allowed per day. Default value would be 2 3 cycles/day.
12. **Actual Cycle (0-100%) count per day (number):** It is the number of round-trip cycles of BESS exhausted at any point of time in the day, after 0000 hrs of that day. If the Actual Cycles count becomes equal to or greater than Scheduled Cycle count, then AGC software would stop sending AGC signals to BESS.
13. **BESS forbidden zones:** Information regarding any forbidden zones in which BESS should not be operated.
14. **AGC Set Point MW from SLDC to BESS:** This is the signal from SLDC to BESS, for the purpose of AGC control. This signal would contain the components of Scheduled MW and a correction corresponding to Area Control Error (ACE), and honours the limits mentioned above. The set point would be positive value while discharging, and negative value while charging.

The following signals would also be needed for monitoring purpose:

1. Actual MVAR
2. Auxiliary Consumption MW
3. BESS Temperature
4. Ambient Temperature
5. Voltage (kV) at grid level
6. Voltage (V) at BESS LV side
7. Feedback/handshake signals
8. Primary Response MW
9. Primary Response ON/OFF status
10. Tap position
11. State of Health (%)

4.4.3 Logics for handling SOC and Cycles in BESS

The Grid India, in its draft paper “Automatic Generation Control of REGS, BESS, and PSP in India”, has provided the following control and monitoring logics for

implementation at both the BESS and NLDC levels. These logics aim to ensure effective supervision and management of the Battery Energy Storage System (BESS), with a specific focus on accurately tracking State of Charge (SOC) and cycle count.

a. SOC Calculation

$$SOC(t) = SOC(t - 1) + \Delta SOC(t)$$

Where:

- SOC(t) is the State of Charge in MWh at time t.
- RTE is the round trip efficiency in percentage (AC-AC)
- SOC(t - 1) is the State of Charge at the previous time step (t - 1).
- $\Delta SOC(t)$ is the change in State of Charge at time t.
- $\Delta SOC(t)$ can be calculated by integrating the net power flow into or out of the system over a specific time interval (Δt). This formula assumes the state of health (SOH) of the BESS as 100%. In other words:

$$\Delta SOC(t) = \int [P_{charge}(t) * RTE - P_{discharge}(t)] dt$$

If instead of RTE, charging efficiency (η_c) and discharging efficiency (η_d) are separately available, then

$$\Delta SOC(t) = \int [\eta_c P_{charge}(t) - \frac{P_{discharge}(t)}{\eta_d}] dt$$

Where $RTE = \eta_c * \eta_d$]

SOC_cycle in MWh is defined as the total energy associated with fully charging and then fully discharging the BESS.

For example, for a BESS rated at 250 MW / 500 MWh, the SOC_cycle for one complete cycle corresponds to the total energy associated with fully charging and then fully discharging the BESS. Since the battery has an energy capacity of 500 MWh, the energy involved in one full charge and one full discharge amounts to 500 MWh each, resulting in a SOC_cycle of $500 \times 2 = 1000$ MWh for a single cycle.

b. Cycle Detection Logic

Cycle: means the charging of a Battery from its Depth of Discharge (DOD) level to its peak charging level (or rated SOC) and again discharging to its DOD level.

Maximum Daily Cycles: The pilot is designed for an **average of 3 daily cycles with a maximum of 5 cycles per day**. If the cumulative throughput in a single day reaches the 5-cycle threshold (12.5 MWh discharge), the EMS shall signal the SLDC and curtail

the AGC response for the remainder of the day to protect the battery chemistry from aggressive degradation.

Depth of Discharge (DOD): means the level to which a BESS is discharged relative to the maximum possible amount of energy that can be discharged by the system, typically expressed as a percentage.

Partial Cycle: Each change in SOC, whether an increase or a decrease, results in a partial cycle. The magnitude of a partial cycle can be estimated using the formula:

$$\text{Partial Cycle} = \Delta \text{SOC} / \text{SOC}_{\text{cycle}}$$

Total Cycle Count: The total cycle count of the BESS is the sum of all partial cycles accumulated over time.

Table 3: Operational Logic Based on SOC and Cycle Count

Sr no	Condition	Cap_Max	Cap_Min	Local/Remote Statue
1	If Actual SOC% = Maximum State of Charge SOC % or 100%	Cap_Max	0	Remote
2	If Actual SOC% = Minimum State of Charge SOC % or 0%	0	Cap_Min	Remote
3	If Cycle Count > Scheduled Cycle Count	0	0	Local

Condition 1: If the SOC% reaches its maximum (100%), the system will set Cap_Max and disable further charging (Cap_Min = 0). The control system can still remain under remote status. The BESS can respond only to discharging commands from AGC software of SLDC.

Condition 2: If the SOC% reaches its minimum (0%), the system will set Cap_Min and disable discharging (Cap_Max = 0). The control system can still remain in remote status.

Condition 3: If the cycle count exceeds the scheduled number of cycles (say, reaches a threshold of 3), the system switches to local status. The BESS only needs to monitor and does not need to respond to the signals from the AGC software of SLDC.

4.4.4 Operational Priority

1. **Secondary Reserve (SRAS):** Primary priority for the 5 MW capacity via 4-second AGC signals.
2. **Primary Reserve (PRAS):** Optional high-speed frequency response (up to 5% capacity) via local frequency sensing.

3. **SoC Maintenance:** Low-priority background task to return the battery to 50% during grid stability periods.

5.0 Energy Accounting & Commercial Settlement Mechanism

The commercial settlement for a BESS-based SRAS involves the fixed service fee payments and variable energy accounting. As the BESS acts as a bidirectional grid element controlled by the AGC signal in real time, the following energy accounting and settlement framework is envisaged.

5.1 Commercial Settlement Mechanism

5.1.1 Service Fee

Since this pilot envisages the “*Storage as a Service*” model, the service provider will be paid a **fixed service fee (₹/MW/Month)**, based on achieving minimum availability. The **minimum monthly guaranteed availability shall be 95%**. The fixed service charges shall be reduced proportionally for the availability <95% and up to 90%. If the actual monthly Availability is less than 90%, a penalty of 1.25x the Fixed Service Charge/Fee on the shortfall duration shall apply.

Table 4: Availability metrics and service fee payment

Sr No	% Availability	Service Fee
1	≥ 95%	100% Service Fee
2	≥90% and <95%	Service Fee x %Actual Availability
3	<90%	(Service Fee x %Actual Availability) Plus (1.25x service fee on shortfall)

5.1.2 Availability

The Service provider Availability will be calculated as the Weighted Capacity Availability for each settlement period (month):

$$\% \text{ Availability} = \frac{\sum_{i=1}^{12} \text{Capacity}(i) \times \text{Hours}(i)}{\text{Contract Capacity} \times \text{Total Hours in Month}}$$

Where:

- Capacity(i) is the available capacity in MW during period (i).
- Hours (i) is the duration of period (i) in hours.
- Contracted Capacity is 5 MW.
- To ensure fairness, any period where the Grid is unavailable shall be treated as "Deemed Available" at the full contracted capacity (5 MW).

Illustration: To clear any ambiguity regarding partial performance, consider the following 30-day month (720 hours) scenario:

Scenario: String-1 (2.5 MW) remains fully functional throughout the month. String-2 (2.5 MW) suffers a technical failure and is unavailable for 15 days (360 hours).

String-1 Availability: $2.5 \text{ MW} \times 720 \text{ hrs} = 1800 \text{ MW-h}$

String-2 Availability: $2.4 \text{ MW} \times 360 \text{ hrs} = 900 \text{ MW-h}$

Total Actual Available: 2,700 MW-h

Monthly Availability = $2700 / (5 \text{ MW} \times 720 \text{ hrs}) = 75\%$

Fixed Service Fee Payment: Since Availability is 75%, the monthly payment is reduced to 75% of the quoted Fixed Service Fee.

PLUS

Penalty Implication: Since 75% is below the 90% Penalty Floor, the shortfall ($95\% - 75\% = 20\%$) will attract a 1.25x penalty on the pro-rata fee for that period.

Performance Penalty Framework

- Stabilization Period (Months 1-3): No extra penalties; only pro-rata reductions apply.
- Operational Period (Months 4-24):
 - 95% to 100%: Full Payment.
 - 90% to 95%: Linear pro-rata reduction of the service fee.
 - Below 90%: Penalty of 1.25x pro-rata fee for shortfall duration.

5.2 Metering

Main and Check Meters: Special Energy Meters (SEMs) (interface meters) shall be installed at the interconnection point, capable of recording active energy in 15-minute time blocks.

Automated Data Flow: SCADA data (sampled every 4 seconds) shall be used for "Accuracy" and "Mileage" verification, while SEM data shall serve as the primary source for financial energy settlement.

5.3 Energy Accounting

Since the BESS is unmanned and automated via SLDC's AGC signals, energy scheduling is not possible in advance. Settlement must be done on an **Ex-Post basis**.

The following three approaches are in Energy Accounting and the settlement of Round-Trip Efficiency (RTE) Losses.

5.3.1 Option-1: Socialized Grid Losses

The BESS is treated as a "Grid Balancing Element" rather than a commercial utility. Hence, for SRAS accounting and settlement, the charging energy for the BESS may be assumed to be arranged by the grid.

Mechanism: The net energy drawl (including charging and RTE losses) is treated as part of the internal state transmission losses. These losses are socialized among all grid users.

Settlement: The Developer receives only the fixed service fee. No separate payment is made for energy drawn or injected.

It is proposed to adopt Option 1 for this pilot project, looking at its insignificant impact on transmission losses as well as to simplify the energy accounting.

5.3.2 Option 2: Net Energy Settlement (Reference Rate Model)

This option aligns with the Methodology suggested by the Grid India², where the Developer is responsible for Round Trip Efficiency (RTE) losses and auxiliary consumption. However, energy settlement shall be made at the compensation rate provided by the SRAS provider.

SRAS-Down (Charging): MWh consumed for downward regulation is refunded by the BESS to the State DSM & Ancillary Services Pool Account at the designated "*Rate of Compensation Charges*."

SRAS-Up (Discharging): MWh injected for upward regulation is paid from the State DSM and Ancillary Services Pool Account to the BESS at the same "*Rate of Compensation Charges*."

RTE Losses: Since the net energy exchange over a regulation cycle is near zero, the ~15% active power loss due to Round Trip Efficiency (RTE) is borne by the BESS. The BESS effectively procures these losses from the grid by paying the net differential into the pool account at the compensation charge, **called the reference rate**.

Payment Mechanism: Settlement is performed on a **Weekly basis** (aligned with state DSM cycles) with a monthly true-up.

² Grid India has published a draft Paper, "Automatic Generation Control of REGS, BESS, and PSP in India, wherein section 3.15 discusses about the accounting and settlement of BESS under AGC

Settlement logic:

$$Net\ energy\ E_{net} = \sum (Energy\ Discharge - Energy\ Charge))$$

Payment settlement

- If $E_{net} > 0$ (Net Injection): The Developer /BESS Service provider shall be receivable at the reference rate.
- If $E_{net} < 0$ (Net Drawl): The BESS Service provider / Developer pays the State Deviation Pool Account (or the BESS pool account) at the Reference Rate.

Currently, the Gujarat SLDC does not procure ancillary services, which means there is no dedicated **ancillary service pool account**. However, the SLDC does maintain a DSM pool account. Any procurement of Secondary Reserves Ancillary Services (SRAS) would ultimately help reduce the control area's deviations, and these costs could be adjusted against the DSM pool account. That said, this adjustment would require approval from the State Regulator, making it an unsuitable option for the pilot project.

6.0 Cost-Benefit Analysis

Any R&D pilot project involves both capital and operational costs. This Pilot project is funded by the Government of Gujarat (GoG). By utilizing the state grant to cover operational expenses, specifically for fixed service fees to be paid to the BESS service provider, this project aims to operate as a Regulatory Sandbox. The primary goal is to gather valuable operational and commercial insights that will help establish a comprehensive regulatory framework for the state. This framework is designed to enhance grid security and stability, specifically by enabling the State Load Dispatch Centre (SLDC) to procure essential secondary reserves in the short term.

Although the primary objective of BESS operation is to provide SRAS to reduce the Area Control Error (ACE) of the Gujarat control area, its sub-second response directly impacts the state's deviation at the periphery. By providing critical active power support during volatile grid conditions, the BESS effectively "clips" the highest-cost deviation peaks. Since DSM rates are progressively steeper outside the IEGC operating band, the BESS fetches the maximum financial benefits when the system is under the most stress.

6.1 Simulation Analysis and Estimated DSM Savings

A detailed simulation was conducted using 15-minute time-block data of the Gujarat State Periphery for the entire year of 2025. The high-resolution deviation data for the Gujarat Control Area was sourced directly from the Western Regional Power

Committee (WRPC) website. The analysis evaluates BESS performance across two different ACE Dead-Band scenarios to get insights about the total number of cycles operated, maximum and average daily cycles, RTE losses and impacts on DSM charges. This is summarized in the Table.

Table 5: Sensitivity analysis of the ACE band

Parameter	ACE Band $\pm$ 200 MW	ACE Band $\pm$ 350 MW
Average Cycles per Day	3.30	1.97
Max Cycle/Day	8.49	3.38
Total Cycles in Year	970	578
Charging Losses (MWh)	429	255
Value of Losses @ ₹ 4.7/unit	₹ 20 Lakhs	₹ 12 Lakhs
Savings in DSM Charges	₹ 91 Lakhs	₹ 85 Lakhs
Net Savings	₹ 71 Lakhs	₹ 73 Lakhs

The simulation demonstrates that the value of DSM penalty avoidance is significantly higher than the cost of energy losses. The cost of energy losses at the Gujarat periphery is taken as the weighted average Deviation Settlement Mechanism (DSM) rate for the Gujarat Control Area, computed from the exhaustive WRPC annual dataset for 2025. For the year 2025, it works out to **₹ 4.70 per unit**. The rationale for considering the DSM rate as the value of grid losses stems from the BESS's real-time operational profile. The BESS dynamically injects or absorbs power in response to AGC signals linked to ACE. Thus, it directly modulates the quantum of energy deviation at the state periphery. Since every instance of charging, discharging, and the consequent energy losses constitutes a direct physical adjustment to the state's DSM energy balance, the average DSM rate serves as the true indicator of the marginal value of these losses, as opposed to the state's Average Power Purchase Cost (APPC), which does not account for the real-time financial volatility of the deviation pool. Consequently, losses in BESS are intrinsically tied to the state's real-time DSM liabilities.

It is important to emphasize that while operational losses are socialized among grid users, the impact is effectively mitigated by the systemic savings; grid users emerge as "net gainers" as the avoided DSM penalties far exceed the cost of socialized grid losses. **Even at a conservative $\pm$ 350 MW band, the net gain in DSM charges is 4x the value of losses (₹ 12 Lakhs)**

6.2 Estimated Cost of Pilot (2 Years)

The total project outlay is calculated based on the fixed service fees (Capacity Charges) required to be paid to the Storage service Provider (BESS Developer) for a 5 MW high-performance asset.

Item	Unit	Rate	Quantity	Amount (₹ Lakhs)
Fixed Service Fee (Capacity Charge)	₹/MW/Month	4,00,000	5 MW x 24 Mon	480.00
Project Management Consultant	Lumpsum			30.00
Total Project Cost (For two years)				510.00

Rationale for Service Fee (Capacity Charge) of ₹ 4.0 Lakhs/MW/Month/

While large-scale BESS price discoveries in India (500 MW+) range between ₹ 2.5 – ₹ 3.0 Lakhs per MW per month, this 5 MW pilot adopts a rate of ₹ 4.0 Lakhs on account of the following considerations.

- **Economies of Scale:** Small-scale projects (5 MW) incur disproportionately higher per-MW costs for 66kV substation interconnection, testing, commissioning and O&M compared to 100 MW+ utility-scale projects.
- **High Power-to-Energy Ratio (2C):** Unlike standard 2-hour storage (0.5C), this AGC pilot requires a high-power 2C BESS. High-power LFP cells and specialized liquid thermal management systems come at a premium compared to energy-dense cells.
- **Contractual Duration:** Due to the shorter 2-year duration, there is a risk of under-recovery of the full Capex of the system.
- **BES Integration & R&D Risk:** The requirement for high-speed (4-sec) AGC handshake and customized EMS software development adds a "Pilot Premium" to the developer's bid.

7.0 Risk Assessment & Mitigation

7.1 Technical & Operational Risks

- **High C-Rate Degradation:** Operating at 2C for AGC causes rapid thermal stress.
- **Mitigation:** Deployment of Tier-1 Liquid Cooling systems and active SoC balancing between modular strings.
- **Thermal Management in Gujarat:** High ambient temperatures (>45°C) can cause PCS de-rating.
- **Mitigation:** Implementation of Option-1 (Modular) with independent cooling and separate kiosks for power electronics.

- **Auxiliary Power Failure:** Loss of AC power to chillers leads to immediate system shutdown.
- *Mitigation:* Redundant 200 kVA Auxiliary Transformers tapped from the 11kV bus.

7.2 Communication & Control Risks

- **SLDC Handshake Latency:** Delays in the 4-second IEC-104 loop can lead to "counter-productive" dispatch.
- *Mitigation:* High-speed fiber connectivity with a dedicated local EMS to handle local "fail-safe" logic if the heartbeat is lost.
- **Heartbeat Loss:** Loss of AGC signal during active regulation.
- *Mitigation:* The BESS shall automatically ramp to "Neutral" (0 MW) or its scheduled baseline if the heartbeat is lost for more than 12 seconds.

7.3 Cybersecurity Risks

- Remote set-point manipulation by unauthorized entities.
- *Mitigation:* Deployment of hardware-based firewalls (OPDS) and end-to-end encryption compliant with CEA Cybersecurity Guidelines 2021.