Hazard Mitigation Analysis

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Contents

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1 Terms and Definitions

Term	Definition
HMA	Hazard Mitigation Analysis
ESS	TeraStor Energy Storage System
ESS unit	One of the four enclosures of the modular TeraStor ESS design.
PCS	Power Conversion System (inverter)

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2 TeraStor HMA

2.1 Background and Scope

The following is the AESI Inc. internal Hazard Mitigation Analysis (HMA) in accordance with 2023 NFPA 855 Standard for the Installation of Stationary Energy Storage Systems §4.4 Hazard Mitigation Analysis.

This report provides findings from the HMA that was performed to assess the anticipated overall effectiveness of:

- protective barriers in place to mitigate the consequences of a battery related failure on-site.
- This analysis was performed based on the latest design.

2.2 Applicable Codes and Standards

This hazard mitigation analysis is conducted in accordance with 2023 NFPA 855 §4.4 Hazard Mitigation Analysis and evaluates the consequences of the following fault conditions required per §4.4.2.1:

1. A thermal runaway or mechanical failure condition in a single ESS unit.
2. Failure of an energy storage management system or protection system that is not covered by the product listing failure modes and effects analysis (FMEA).
3. Failure of a required protection system including, but not limited to, ventilation (Chiller), exhaust ventilation, smoke detection, fire detection, or gas detection.

Additionally, for completeness, this report also includes two additional failure modes required per 2021 International Fire Code (IFC) §1207.1.4.1:

4. Voltage surges on the primary electric supply.
5. Short circuits on the load side of the ESS.

Per NFPA 855 §4.4.3 Analysis Approval, the AHJ shall be permitted to approve the hazardous mitigation analysis as documentation of the safety of the ESS installation provided the consequences of the analysis demonstrate the following:

1. Fires will be contained within the ESS enclosure for the minimum duration of the fire resistance rating specified.
2. Fires and products of combustion will not prevent occupants from evacuating to a safe location.

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3. Deflagration hazards will be addressed by an explosion control or other system.

The following key codes, standards, and local requirements are referenced throughout the report:

- NFPA 855 Standard for the Installation of Stationary Energy Storage Systems, 2023 Edition
- UL 9540A Standard for Test Method for Evaluation Thermal Runaway Fire Propagation in Battery Energy Storage Systems, 4th Edition
- UL 9540 Standard for Energy Storage Systems and Equipment, 3rd Edition
- UL 1973 Standard for Batteries for Use in Stationary and Motive Auxiliary Power Applications, 3rd Edition
- UL 1741 Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources, Edition 3, Oct 2022

2.2.1 Summary of HMA Findings

Based on review of documentation provided by AESI at the time of this writing, ESRG finds that adequate protections are provided for the fault conditions listed per 2023 NFPA 855 §4.4.2.1 and analysis approval requirements per §4.4.3. Key findings include:

- The TeraStor ESS is modular and factory assembled with prevention and protection systems (e.g., insulated enclosures, deflagration control system consisting of overpressure vents and sparker system, liquid chilled cold plates for direct thermal management of battery modules, remote and manual electrical shutdowns and disconnects, automated BMS controls, integrated EMS, etc.) that designed to effectively manage all applicable fault conditions required per NFPA 855 §4.4.2.1 and IFC §1207.1.4.1.
- TeraStor ESS project is compliant with all applicable Analysis Approval requirements per NFPA 855 §4.4.3.
- Preliminary UL 9540A full-scale fire testing and performance of the TeraStor ESS has shown that the system can be installed without the need for any additional passive or active fire protection features to prevent unit to unit propagation. Additionally, performance during UL 9540A testing indicates that nearby exposures will not be largely affected in the event of an ESS-related failure on-site. Minimum separation distance of less than 3 feet are expected.

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- AESI has conducted additional voluntary destructive testing on TeraStor ESS with aggressive approaches beyond standard testing to force battery modules into thermal runaway. The results of this testing showed that – TeraStor system design made it difficult to initiate any thermal runaway within the ESS unit.
- The following TeraStor documentation is available for additional review:
  - Emergency Response
  - Operation Guide
  - ASEI Component Sheet for fire panel and detection systems
    - Optional Dry pipe fire suppression may be used but is not required

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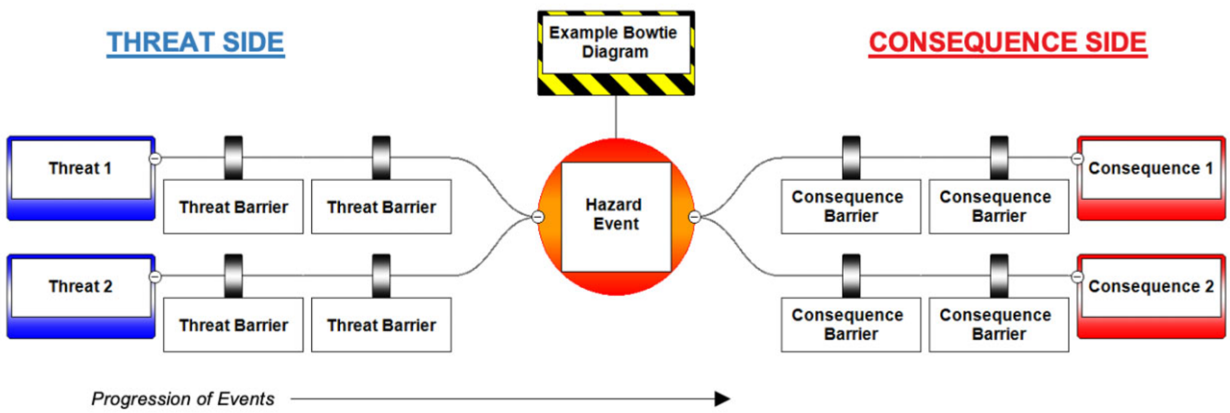
3 Hazard Mitigation Analysis

3.1 Methodology

The HMA utilizes the bowtie methodology for hazard and risk assessments, as is described in 2023 NFPA 855 Section G.3.6. It allows for in-depth analysis on individual mitigative barriers and serves as a tool for visualizing the pathway of threats leading to critical hazard events, and ultimately to greater potential consequences (see figure below). This simple way of describing and analyzing the pathways of a risk from hazards to outcomes can be considered to be a combination of the logic of a fault tree analysis combined with the cause of an event and an event tree analyzing the consequences.



Each fault condition per NFPA 855 and IFC assessed in the following sections below is is detailed in the corresponding tables, indicating critical threat and consequence pathways and the mitigative barriers between them. These tables can be used to generate the bow tie diagrams.

As the most critical risk posed by lithium-ion battery cells comes from the propagation of thermal runaway from a failing cell (or multiple cells) to surrounding cells, this serves as the primary critical hazard for the subsequent failure scenarios.

In addition to main barriers for fault conditions on the threat side of the diagram, the consequence barriers on the right side of the diagram (e.g., explosion protection and emergency response plan) also contribute added layers of safety on top of the main threat barriers shown. It is important to note that the barriers on the left side, along a threat path, are intended to keep the threat from becoming a thermal runaway, while the barriers on the right side, along the consequence pathway, are intended to keep that single thermal runaway from evolving into one of the more severe

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consequences such as off-gassing leading to explosion, or fire spread beyond containment.

3.2 Fault Condition Analysis Summary

Per NFPA 855 §4.4.2.1, the analysis shall evaluate the consequences of the following failure modes and others deemed necessary by the AHJ:

1. A thermal runaway or mechanical failure condition in a single ESS unit
2. Failure of an energy storage management system or protection system that is not covered by the product listing failure modes and effects analysis (FMEA)
3. Failure of a required protection system including, but not limited to, Liquid cooling (Chiller), smoke detection, fire detection, fire suppression, or gas detection.

This report also includes two additional failure modes required per 2021 International Fire Code (IFC) §1207.1.4.1:

4. Voltage surges on the primary electric supply
5. Short circuits on the load side of the ESS

For the purposes of this report, only single failures modes shall be considered for each mode given above. Additionally, it shall be assumed that all construction, equipment, and systems that are required for the ESS shall be installed, tested, and maintained in accordance with local codes and the manufacturer's instructions. The assessment is based on the most recent design information at the time of this evaluation.

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The following table provides a summary of findings from the hazard mitigation analysis performed in fulfillment of NFPA 855 §4.4.2.1 and IFC §1207.1.4.1. Detailed descriptions of fault conditions specified per NFPA 855 and IFC are also provided in the following sections.

Table 1

Compliance Requirement	Comments
1. A thermal runaway or mechanical failure condition in a single ESS unit	Several passive and active measures are implemented to reduce the potential of a thermal runaway event from occurring including BMS control and active cooling to internal components. Battery modules and cells have been listed to UL 1973 and tested to UL 9540A. Should a thermal runaway event occur, additional mitigative measures are provided to prevent further propagation of failure throughout the system (see for list of all consequence barriers).
2. Failure of an energy storage management system or protection system that is not covered by the product listing failure modes and effects analysis (FMEA)	In the event of a failure of the system level BMS, the EMS and Stor-View application will detect a loss of connection and alert the Site operator. BMS fault notifications shall be transmitted to remote 24/7 Network Operations Center (NOC), alerting system owner to abnormal conditions. Data from the BMS may be communicated to project SMEs to provide guidance to the fire department in case of emergency. To further isolate any failure stemming from a failure of the energy storage management system, passive and active electrical fault protections are provided at multiple levels, as described in respective sections of this report. A failure of the BMS or related block monitor, Cell interface boards, will result in a System shutdown.

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Compliance Requirement	**Comments**
3. Failure of a required protection system including, but not limited to, ventilation (HVAC), exhaust ventilation, smoke detection, fire detection, fire suppression, or gas detection	**Failure of Exhaust Ventilation** The TeraStor **does not utilize** an exhaust ventilation system, instead using a passive sparker system for gas elimination and overpressure vents for explosion control. **Failure of Smoke Detection** The system includes redundant smoke detectors. The Fire panel will detect the failure of a smoke detector which will alarm the BMS and trigger audible siren and visual strobes on the unit. BMS fault notifications shall be transmitted to remote 24/7 Network Operations Center (NOC), alerting system owner to abnormal conditions. Data from the BMS may be communicated to project SMEs to provide guidance to the fire department in case of emergency. . **Failure of Fire Detection** Should IR detection systems fail, it is anticipated that BMS fault notifications shall be transmitted to remote 24/7 Network Operations Center (NOC), alerting system owner to abnormal conditions. Data from the BMS may be communicated to project SMEs to provide guidance to the fire department in case of emergency. **Failure of Fire Suppression System:** The TeraStor does not utilize fire suppression (either water- based or non-water-based), instead using sparker system to eliminate off-gasses before an explosive condition is allowed to accumulate within the enclosure. The Emergency response plan (ERP) details what actions to take in case of an event. Furthermore, UL 9540A Unit level testing indicates that no flaming occurred and that no propagation of heat from the initiating unit to adjacent units / modules reached levels capable of initiating cell venting or thermal runaway. **Failure of Gas Detection** The system includes redundant gas detectors. The Fire panel will detect the failure of a gas detector which will alarm the BMS and trigger audible siren and visual strobes on the unit. BMS fault notifications shall be transmitted to remote 24/7 Network Operations Center (NOC), alerting system owner to abnormal conditions. Data from the BMS may be communicated to project SMEs to provide guidance to the fire department n case of emergency.

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Compliance Requirement	Comments
4. Voltage surges on the primary electric supply *(IFC §1207.1.4.1(4))*	Voltage surges on the primary electric side are mitigated by the provided UL 1741 compliant Power Conversion System (PCS), BMS and inverter controls, voltage monitoring and automatic disconnect provided by the BMS, in addition to a number of passive circuit protections noted in respective sections of this report.
5. Short circuits on the load side of the ESS *(IFC §1207.1.4.1(5))*	Short circuits on the load side of the ESS are mitigated by BMS control and PCS and subsequent safety actions, in addition to a number of passive circuit protections noted in respective sections of this report. The Terastor includes current limiting devices on the internal DC bus.

Table 2: Consequence Barriers

PRIMARY CONSEQUENCE BARRIERS	
Battery Management System (BMS)	TeraStor BMS provides automatic monitoring, charge, and safety features including disablement. BMS monitoring automatically completes safety activity including e-Stop and notifies operators proactively in case of abnormal sensor readings via StorView. StorView monitoring communication is a critical safety function. TeraStor BMS will activate a safety E-Stop if communications are lost. The BMS monitoring includes Supercell over voltage, over discharge, Supercell over temperature, sensor signal loss, cell string over voltage, over-discharge, and battery string over-current. BMS activity is logged and displayed with StorView dashboards with clear and actionable notifications to operators for preventative oversight. Each of the four "Quarter blocks" is insulated and has monitors for safety and environment controls. Other sensors and detectors installed include communication, smoke and gas detection, sparker health, standing water, temperature, voltage, chiller fluid pressure, and humidity. The BMS will trigger a shutdown of the PCS followed by the motorized DC disconnect if an out of tolerance condition is detected.
Fire Detection	TeraStor fire safety systems are NFPA 855 compliant and includes an NFPA 72 compliant fire panel that is connected with a dedicated line to the site fire control system. It utilizes three smoke detectors and two gas detectors inside each Quarter Block of the TeraStor.

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Deflagration Protection	TeraStor includes deflagration protection in the form of pressure-sensitive vents and a gas elimination sparker system, designed to ignite and eliminate any flammable gases before gasses can accumulate at a level that would create an explosion risk.
Electrical Fault Protection Devices	TeraStor electrical fault protection is built into the redundant sensors and BMS safety control with battery module overcurrent protection, inverter DC and AC protection, and ground fault protection.
Facility Design and Siting	This is Site specific and will vary based on installation.
Emergency Response Plan / First Responders	A site-specific Emergency Response Plan (ERP) is developed by the purchaser with guidance from TeraStor Emergency Response documentation.
BMS Data Availability / Network Operations Center (NOC)	BMS is available remotely via 24/7 Network Operations Center (NOC) to AESI and site operators. BMS data is available real-time for authorized site personnel and AESI team in StorView. Data warehouse access is available via StorView Cloud. Local Emergency response personnel can be issued login to help guide response in the event of an emergency on-site.
Fire Service Response	Site Specific : "Example: The nearest fire station (NAME) is located approximately (DISTANCE) from the site."

3.2.1 Thermal runaway

Thermal runaway is defined as the condition when an electrochemical cell increases its temperature through self-heating in an uncontrollable fashion and progresses when the cell's heat generation is at a higher rate than it can dissipate, potentially leading to off- gassing, fire, or explosion. The cause of a thermal runaway event can range from a manufacturer defect in the cell, external impact, exposure to dangerously high temperatures, or a multitude of controls and electrical failures. Furthermore, a thermal runaway event in a single cell can propagate to nearby cells, thus creating a cascading runaway event across battery modules and racks, leading to more heat generation, fire, off-gassing, and increased potential for a deflagration event.

TeraStor's passive and active mitigations such as thermal insulation between Cells, Monitoring and Control from the BMS, and its active thermal management system for

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cooling of cells and components, reduce the potential of a thermal runaway event from occurring. Threat scenarios accounted for include single-cell thermal runaway, multi-cell thermal runaway, and internal defect or failure not resulting in thermal runaway, leading to the primary hazard event (propagating cell failure leading to off-gassing or fire).

Should thermal runaway occur within a battery module, a number of key barriers are provided to mitigate against propagation of failure throughout the system leading to more severe consequences.

Table 3

Barrier	Barrier Description
THREAT BARRIERS	
Battery Management System (BMS)	The BMS provides sensing and control of critical parameters and triggers protective or corrective actions if the system is operating out of normal parameters. These Parameters include Supercell over-voltage, over-discharge, Supercell over-temperature, cell string over-voltage, cell string over-discharge, voltage, temperature signal loss, and System over current. In the event of any abnormal conditions, the BMS will first raise an information warning and then trigger a corresponding corrective action should certain levels be reached. For significant out-of-tolerance conditions the PCS is shutdown disconnecting the grid, and then the DC disconnect is opened isolating the battery string.
Thermal Management System	Active thermal management system provides liquid cooling to internal components within the TeraStor to limit heat diffusion.
Cell Thermal Abuse Tolerance	Cell has been tested and listed to UL 1973 in which thermal abuse tolerance was tested. Cell has been evaluated to UL 9540A
Supercell Thermal Abuse Tolerance	Supercell has been evaluated to UL 9540A. System level testing and listing to UL1973 includes cell-string level.
CONSEQUENCE BARRIERS	

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See Table 2 above for a list of primary consequence barriers.

3.2.2 Failure of an Energy Storage Battery Management System

The loss, failure, or abnormal operation of an energy storage control system (controllers, sensors, logic / software, actuators, and communications networks) may directly impact the proper function of the system. The TeraStor utilizes a tiered hierarchy of controls starting at the Supercell level up to the site level.

The TERASTOR BMS automatically initiates E-Stop and notification actions in case of sensor status or detector with abnormal operation outside of set parameters. This shuts down the PCS and opens the DC disconnect, isolating it from the grid first and then isolating the battery string.

To further isolate any failure stemming from a failure of the energy storage battery management system, passive and active electrical fault protections are provided at multiple levels, as described in the following sections.

Table 4: BMS failure

Barrier	**Barrier Description**
THREAT BARRIERS	
Battery Management Systems (BMS)	BMS provides supervisory actions and isolation / protective actions in case of component failure.
System Shutdown / Disconnect	Multiple levels of passive and active electrical protections are provided by the TeraStor including module overcurrent protection via fusible links on the DC Bus, PCS DC and AC protections, and ground fault detection, safety interlocks, manual disconnect, Motorized DC disconnect, and other “fail-safe” mechanisms.
Passive Circuit Protection and Design	Fused disconnects and DC disconnect switches, in addition to ground fault detection / interruption and over voltage protection provided.
Cell Electrical Abuse Tolerance	Cell tested and certified to UL 1973 Standard for Lithium Batteries. Cells tested to UL 9540A
CONSEQUENCE BARRIERS	

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See Table 2 above for list of primary consequence barriers.

3.2.3 Failure of a Required Ventilation or Exhaust System

Lithium-ion batteries do not release flammable gas during normal operations. The TeraStor does not utilize a ventilation or exhaust system for this reason.

3.2.4 Failure of a Required Smoke Detection, Fire Detection, Fire Suppression, or Gas Detection System

The fire panel will signal the BMS if there is a fault with a smoke detector and/or gas detector.

Failures beyond a safe threshold will trigger a system shutdown. BMS fault notifications will be transmitted to remote 24/7 Network Operations Center (NOC), alerting system owner(s) to abnormal conditions. Data from the BMS may be communicated to project SMEs or corporate first responders to provide guidance to the fire department in case of emergency.

The TeraStor does not rely on a fire suppression system (either water-based or non-water-based). Fire is not expected to propagate through the system or to nearby exposures based on UL 9540A Unit level testing indicating that no flaming occurred and that no propagation of heat from the initiating unit to adjacent units / modules reached levels capable of initiating cell venting or thermal runaway.

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Table 5 - Failure of Smoke Detection, Fire Detection, Fire Suppression, or Gas Detection System Barriers

Barrier	Barrier Description
CONSEQUENCE BARRIERS	
Battery Management System (BMS)	BMS provides sensing and control of critical parameters and triggers protective or corrective actions if system is operating out of normal parameters. Parameters include Super Cell over-voltage, over-discharge, Super Cell over temperature, cell string over- voltage, over-discharge, temperature signal loss, and Super Cell over current. In the event of any abnormal conditions, the BMS will first raise an information warning and then trigger a corresponding corrective action should certain levels be reached.
Deflagration Protection	The TeraStor is equipped with deflagration protection in the form of pressure-sensitive vents and sparker ignition system. The system is designed to ignite and eliminate any flammable gases in a controlled manner before they are allowed to accumulate and create an explosive atmosphere within the enclosure. Pressure sensitive panels provide additional redundant protection.
Thermal Isolation / Cascading Protection	Thermal isolation has been shown to be effective in limiting heat transfer between Supercells in UL 9540A module and unit level preliminary testing. This testing showed no additional propagation beyond the target cell.
Facility Design and Siting	Site specific information - Outdoor ground mounted environment, restricted access.
Emergency Response Plan / First Responders	A general Emergency Response Plan (ERP) will be developed that can be used for the development of a site-specific Emergency Response Plan (ERP).

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BMS Data / Network Operations Center (NOC)	BMS is available remotely via 24/7 Network Operations Center (NOC). This data shall be communicated to the designated SMEs and emergency response personnel to help guide response in the event of an emergency on-site.
Fire Service Response	For example: The nearest fire station details / distance

3.2.5 Voltage Surges on the Primary Electric Supply

Voltage surges on the primary electric supply are expected to be largely mitigated by voltage monitoring and corrective actions taken by the BMS and design of the Power conversion system. Should corrective actions initiated by the BMS fail to prevent further propagation of failure, a number of electrical fault protections are provided for the Terastor, as are briefly described in Table 2 of this report.

Table 6 - Voltage Surges on the Primary Electric Supply Barriers

Barrie r	Barrier Description
THREAT BARRIERS	
Voltage Monitoring	Voltage is measured by BMS, triggering fault and alarm monitor indicators, and potential system disconnect or other corrective actions if operating out of normal parameters.
System Shutdown / Disconnect	Multiple levels of passive and active electrical protection are provided which include module overcurrent protection via fusible links on the DC side of the modules, inverter DC and AC protections, and ground fault detection.
Battery Management System (BMS)	BMS provides sensing and control of critical parameters and triggers protective or corrective actions if a system is operating out of normal parameters. Parameters include battery module over / under voltage, cell string over-voltage,

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	over-discharge, battery module over temperature, temperature signal loss, and battery module over current. In the event of any abnormal conditions, the BMS will first raise an information warning and then trigger a corresponding corrective action should certain levels be reached.
Inverter / PCS Controls	Inverter modules equipped with Surge protection devices on the AC input, both DC protection via high-speed pyrotechnic fuse for passive or active isolation of battery module, as well as dedicated AC contactor and AC fuses should an abnormal electrical event occur at the inverter module on the AC side of the circuit.
Passive Circuit Protection / Design	Current limiting fuses and DC disconnect switch, in addition to ground fault detection / interruption and over voltage protection provided.
System Electrical Abuse Tolerance	System tested and listed to UL 1973, and UL9540.
CONSEQUENCE BARRIERS	
See Table 2 for list of primary consequence barriers.	

3.2.6 Short Circuits on the Load Side of the ESS

Short circuits on the load side of the ESS are anticipated to be largely mitigated by BMS control and passive circuit protection and design (e.g., fused disconnects, ground fault detection / interruption, and overvoltage / overdischarge protection), as described in previous sections of this report. The system will be tested and listed to UL 9540 and UL 1973.

Should propagating thermal runaway occur, a number of key barriers are provided to mitigate against propagation of failure

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throughout the system leading to more severe consequences, which are described in detail in Table 2 of this report above.

Table 7 - Short Circuits on the Load Side of the ESS Barriers

Barrier	Barrier Description
THREAT BARRIERS	
Battery Management System (BMS)	BMS provides sensing and control of critical parameters and triggers protective or corrective actions if a system is operating out of normal parameters. Parameters include Supercell over / under voltage, cell string over / under voltage, Supercell over temperature, temperature signal loss, and battery module over current. In the event of any abnormal conditions, the BMS will first raise an information warning and then trigger a shutdown of the PCS and open the DC disconnect, should certain levels be reached.
Voltage Monitoring	System voltage and cell voltage is measured by BMS, triggering fault and alarm monitor indicators, and potential system disconnect or other corrective actions if operating out of normal parameters.
System Shutdown / Disconnect	Multiple levels of passive and active electrical protections are provided for the TeraStor including system overcurrent protection via fusible links on the DC side of the modules, inverter DC and AC protections, and ground fault detection.
Passive Circuit Protection / Design	Current limiting fuses, and DC disconnect switch, in addition to ground fault detection / interruption and over voltage protection provided.

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System Electrical Abuse Tolerance	System tested and listed to UL 9540, and UL 1973.
CONSEQUENCE BARRIERS	
See Table 2 above for list of primary consequence barriers.	

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3.3 APPENDIX – REFERENCED CODES AND STANDARDS

- NFPA 855 Standard for the Installation of Stationary Energy Storage Systems, 2023 Edition
- UL 9540A Standard for Test Method for Evaluation Thermal Runaway Fire Propagation in Battery Energy Storage Systems, 4th Edition
- UL 9540 Standard for Energy Storage Systems and Equipment, 2nd Edition
- UL 1973 Standard for Batteries for Use in Stationary and Motive Auxiliary Power Applications, 3rd Edition
- UL 1741 Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources, 3rd Edition

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Revision History

Rev.	Description	Author(s)	Date
1.0	Draft template	M. Sullivan	11/17/2023
1.1	Added details of HMA analysis	M,. Anderson	1/30/2024

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