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Preface

This Standard was prepared by the Rolling Stock Onboard Electrical Energy Storage Development Group, overseen by the ARISO Rolling Stock Standing Committee.

Objective

The objective of this document is to provide guidance to rail transport operators (RTOs) for the specification and utilization of onboard batteries and electric double-layer capacitors (EDLC) used for traction purposes (propulsion and braking).

This document provides guidance to ensure that they are used safely, effectively and reliably in the Australian context and networks, throughout the life of the energy storage system (ESS). This document provides a basis for RTOs, vehicle manufacturers and ESS manufacturers to understand and communicate the requirements on ESS.

The document provides guidance and an understanding of:

(a) ESS design principles to support safety and reliability;

(b) the ESS's through life assessment factors;

(c) the ESS testing and certification requirements;

(d) the hazards and risks associated with the ESS integration into vehicles;

This document builds on existing national and international standards by providing additional guidance and requirements for ESS. See Appendix B for a summary of system and subsystem levels applicable to these standards.

Performance based requirements, recommendations and guidance do not replicate existing published requirements and recommendations.

Compliance

There are four types of provisions contained within Australian Standards developed by ARISO:

(a) Requirements.

(b) Recommendations.

(c) Permissions.

(d) Constraints.

Requirements – it is mandatory to follow all requirements to claim full compliance with the Standard. Requirements are identified within the text by the term 'shall'.

Recommendations – do not mention or exclude other possibilities but do offer the one that is preferred. Recommendations are identified within the text by the term 'should'.

Recommendations recognize that there could be limitations to the universal application of the control, i.e. the identified control is not able to be applied or other controls are more appropriate or better.

For compliance purposes, where a recommended control is not applied as written in the standard it could be incumbent on the adopter of the standard to demonstrate their actual method of controlling the risk as part of their WHS or Rail Safety National Law obligations. Similarly, it could also be incumbent on an adopter of the standard to demonstrate their method of controlling the risk to contracting entities or interfacing organisations where the risk may be shared.

Permissions – conveys consent by providing an allowable option. Permissions are identified within the text by the term 'may'.

Constraints – provided by an external source such as legislation. Constraints are identified within the text by the term ‘must’.

ARISO Standards address known hazards within the railway industry. Hazards, and clauses within this Standard that address those hazards, are listed in Appendix A.

Appendices in ARISO Standards may be designated either “normative” or “informative”. A "normative" appendix is an integral part of a Standard and compliance with it is a requirement, whereas an "informative" appendix is only for information and guidance.

Commentary

Commentary *C Preface*

This document includes a commentary on some of the clauses. The commentary directly follows the relevant clause, is designated by ‘C’ preceding the clause number and is printed in italics in a box. The commentary is for information and guidance and does not form part of the Standard.

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Section 1 Scope and general

1.1 Scope

This document provides the general design principles and safety requirements for energy storage systems (ESSs) that use batteries and electric double-layer capacitors (EDLCs) on new and modified rolling stock in Australia. The document focusses on the hazards and risks associated with lithium-ion batteries and EDLCs and their implementation.

1.2 Out of scope

The following is not included in the scope:

(a) Wayside energy storage.

(b) Wayside charging infrastructure excluding on-board interfaces.

(c) Energy storage technologies other than batteries or EDLCs.

(d) Any requirements and recommendations on other systems that are not explicitly related to supporting the ESS function and safety.

1.3 Normative references

The following documents are referred to in the text in such a way that *some* or all of their content constitutes requirements of this document:

- AS 7501:2019, Rolling stock compliance certification
- AS 7507:2017, Rolling stock outlines
- AS 7509:2017, Rolling stock – Dynamic Behaviour
- AS 7520:2023 (all parts), Australian Railway Rolling Stock – Body Structural Requirements
- AS 7529.1:2014, Australian Railway Rolling Stock – Fire Safety
- AS 7530:2018, Electrical systems
- AS 7633: 2020, Railway infrastructure: Clearances
- AS 7722:2026, EMC Management
- IEC 60077-1:2017, Railway applications – Electric equipment for rolling stock – Part 1: General service conditions and general rules
- IEC 61881-3:2012, Railway Applications – Rolling Stock Equipment – Capacitors for power electronics
- IEC 62864-1:2016, Railway Applications – Rolling Stock – Power supply with onboard energy storage system – Part 1: Series Hybrid System: Specifies general requirements for the onboard energy storage system at a system level
- IEC 62928:2018, Railway Applications – Rolling Stock – Onboard lithium-ion
- UL 9540A:2025, Test Method for Battery Energy Storage Systems (BESS)

NOTE:

Documents for informative purposes are listed in a Bibliography at the back of the Standard.

1.4 Defined terms and abbreviations

For the purposes of this document, the following terms and definitions apply:

1.4.1
battery management system (BMS)
system associated with a battery pack which monitors and/or manages its state, disconnects or isolates the battery pack, calculates secondary data, communicates data outside of the battery system and/or controls its environment to influence the battery's safety, performance and/or service life
[SOURCE: IEC 62928:2018, 3.1.29]

1.4.2
battery thermal management system (BTMS)
system associated with a battery pack which monitors and/or manages its thermal behaviour in order to maintain the temperature of the battery pack in the intended range for load profile agreed between the integrator and the battery system manufacturers
[SOURCE: IEC 62928:2018, 3.1.30]

1.4.3
capacitor element
indivisible part of a capacitor consisting of two electrodes (typically made of carbon) separated by an electrolyte impregnated separator
[SOURCE: IEC 61881-3:2012, 3.1]

1.4.4
capacitor cell
one or more capacitor elements, packaged in the same enclosure with terminals brought out
[SOURCE: IEC 61881-3:2012, 3.2]

1.4.5
capacitor module
assembly of two or more capacitor cells, electrically connected to each other with or without additional electronics
[SOURCE: IEC 61881-3:2012, 3.3]

1.4.6
capacitor bank
assembly of two or more capacitor modules
[SOURCE: IEC 61881-3:2012, 3.4]

1.4.7
capacitor
general term used when it is not necessary to state whether a reference is made to capacitor cell, module or bank
[SOURCE: IEC 61881-3:2012, 3.5]

1.4.8
direct current (DC)
electrical current that flows consistently in one direction

1.4.9
EDLC
electric double-layer capacitor
[SOURCE: IEC 62864-1:2016, 3.1.22]

1.4.10
energy storage system (ESS)

physical system which consists of one or more ESUs and the other equipment required to connect to the DC link such as converters, control and monitoring systems, inductors, protection devices, cooling systems, etc.
[SOURCE: IEC 62864-1:2016, 3.1.22]

1.4.11
energy storage unit (ESU)
physical equipment which is comprised of energy storage technologies such as batteries or EDLC
[SOURCE: IEC 62864-1:2016, 3.1.20]

1.4.12
ESS secondary power
energy that has been converted from a primary power source into a transformed form such as electricity

1.4.13
offboard
not installed on the rolling stock

1.4.14
onboard
installed on the rolling stock

1.4.15
ESS primary power
energy generated from the original source such as a diesel generator in a locomotive

1.4.16
rail transport operator (RTO)
As defined in Rail Safety National Law.

1.4.17
shore supply power
system used to provide external electrical energy to rolling stock for powering auxiliaries

1.4.18
through-life
the whole lifecycle of the ESS and its interaction with the vehicle and railway enterprise. This includes considering the ESS's installation, commissioning, operation, maintenance/support and final disposal

General rail industry terms and definitions are maintained in the ARISO Glossary. Refer to: https://www.ariso.org.au/glossary/

Section 2 Energy storage system (ESS) general context

2.1 Applications and purpose of the ESS within rolling stock

An ESS within rolling stock serves a range of operational, safety and performance functions. Its purpose is to store, manage and deliver electrical energy in a controlled manner to support vehicle propulsion, auxiliary loads and system resilience.

Depending on the vehicle type and operational context, the ESS can fulfil one or more of the following applications:

(a) As the primary traction power supply for the rolling stock.

(b) As a secondary traction power supply for the rolling stock, by either or both of the following:

   (i) reducing peak loads on the primary traction power supply by supplementing it during acceleration; and/or

   (ii) providing back-up power supply to increase the availability of rail vehicle systems when other power and propulsion systems or energy sources are unavailable or have limited capacity.

(c) To increase electric traction system efficiency and reduce emissions, either by:

   (i) capturing energy during regenerative braking and making it available during powering. This energy would otherwise be directed to the braking resistors to be converted to heat and lost;

   (ii) allowing for zero emission coasting and idling with other power sources off, by providing an alternative power supply; and/or

   (iii) allowing other power sources, such as diesel engines, to operate at their peak thermal efficiency.

(d) To reduce the amount of track-side electrical infrastructure required in some locations.

(e) As a source to power auxiliary systems on the rolling stock.

The ESS shall be treated as a system within the overall rolling-stock architecture, with clearly defined subsystem levels to support design, integration, safety assurance and lifecycle management. Each level shall have defined functions, interfaces and responsibilities to ensure safe and reliable operation. See Appendix B for a description of the ESS and subsystem levels.

The ESS interacts with multiple systems across the rolling-stock architecture. These interfacing systems shall be identified, defined and controlled to ensure safe, reliable and compliant ESS integration. Interfaces can be electrical, mechanical, thermal, software-based, or operational in nature. See Appendix C for further details of ESS interfacing systems.

Commentary *C2.1-1*

Engine efficiency will often vary with the loading of a diesel engine. ESSs allow for diesel generators to maximize operation at peak efficiency for a longer period by receiving and storing excess power for later use rather than being forced to operate at an operating condition with lower efficiency.

Commentary *C2.1-1*

A reduction in noise is achieved when the ESS is used as the primary power source instead of a diesel engine. This allows for quiet shunting in yards and quiet acceleration from stations. The ESS could also reduce operating noise by allowing diesel-electric trains to minimize the use of maximum engine revolutions or power notch by providing the extra power demand of the traction system.

NOTE:

IEC 62864-1:2016 Section 4 provides a comprehensive description of various onboard ESS configurations and modes of operations for different types of rolling stock.

Section 3 ESS requirements and specification

3.1 Design principles

3.1.1 General design principles

The following design principles apply throughout the life of the ESS to support the safety and reliability of new or modified vehicles in the Australian context:

(a) The ESS and the vehicle it integrates with shall remain safe throughout their entire lifecycle. This includes ensuring they can be safely operated, inspected, maintained, repaired and decommissioned within their intended application and environment.

(b) The ESS shall be specified and designed to reliably fulfil its intended purpose under the environmental, operational and regulatory conditions it will encounter. Its design shall consider every stage of its lifecycle—from concept and manufacture through operation, maintenance and end-of-life.

(c) The ESS specification shall identify and address all relevant through-life factors, including ageing, degradation, environmental exposure, operational stresses and foreseeable misuse. Associated hazards and risks shall be systematically identified, assessed and controlled.

(d) The ESS implementation shall include all necessary requirements to enable the vehicle to meet its own safety, performance and regulatory obligations. This includes ensuring compatibility and safe interaction with vehicle systems and interfaces, as well as any off-board systems such as charging infrastructure, diagnostic tools or fleet-management systems.

3.1.2 The ability of the ESS to tolerate partial failure

The ESS should be designed with appropriate redundancy to ensure that a failure of one or more sub-units does not result in total loss of function, and that critical systems can continue to operate. The following design aspects should be observed:

(a) The thermal performance of the ESS under peak load conditions, including the ability of the cooling system to maintain safe operating temperatures during high power demand and environmental temperature changes.

(b) The inclusion of monitoring systems to track ESS performance over time and support predictive maintenance, including indicators of degradation, energy throughput and thermal stress.

(c) The interaction of the ESS with other on-board or off-board power sources, including diesel-electric or overhead wire systems, ensuring seamless transitions and coordinated control.

The ESS shall incorporate a battery management system (BMS/BTMS) that continuously monitors all key battery parameters, including voltage, current, temperature and state-of-charge (SOC).

The BMS shall be capable of detecting any condition that could lead to unsafe ESS operation and shall automatically initiate appropriate protective action. These actions shall include limiting charge or discharge rates, isolating affected sections or isolating the entire ESS to prevent damage, degradation or the creation of a hazardous situation.

3.1.3 Design principles for functional failure

Design controls for managing ESS functional failure should include, but are not limited to the following:

(a) Maintaining the ESS in accordance with the manufacturer's instructions to maximize system availability, reliability and safe performance throughout its lifecycle.

(b) Incorporating fail-safe mechanisms that ensure the system transitions to, or remains in, a safe state in the event of a power loss or critical fault.

(c) Having redundancy in the power in the power supply to the ESS and associated control systems to ensure continued operation in the event of a power loss, voltage drop or interruption.

(d) Having protection against overcurrent, surges and other abnormal electrical conditions where excessive power or energy might be delivered relative to system requirements.

(e) Incorporating design features and operational protocols that prevent damage to ESS components, including protective hardware, software controls and operational limits Identifying, assessing and eliminating single-point failures where practicable by design.

(f) Allowance for remote isolation from the driver's cabin to support emergency response, maintenance and safe shutdown procedures.

(g) Physical security controls to ensure that only authorized personnel can access the ESS, preventing tampering, misuse or unauthorized intervention.

3.1.4 Design principles for managing human interaction with the ESS

Design controls for managing human interaction with the ESS should include, but are not limited to the following:

(a) Automating the management of the ESS and limiting operator interaction as much as possible to reduce the added complexity of operating the ESS.

(b) Adding safety/warning signs or decals both inside and outside of the battery box as part of the safety requirements.

(c) Identifying any PPE requirements for people accessing and working on the ESS.

(d) Constructing the ESS to ensure that all terminals and connects are protected against short-circuiting due to a dropped tool.

(e) Providing training and instruction to train operators, installers, maintainers and accident responders so that the ESS and the vehicle it is installed in is safe through-life.

(f) Systems for preventing access to parts of the system which do not require access.

(g) Locating the ESS in areas that are accessible to personnel that interact with the system during the life-cycle.

(h) Implementing cybersecurity measures such as software and firewalls to external and internal connections to the ESS.

(i) Installing the ESS so that it does not block all evacuation routes.

(j) Installing the ESS so that it does not create a slip/trip hazard or impede access routes for inspection or accessing serviceable components.

(k) Providing a data interface for diagnostic work that can be undertaken either onboard, or through the vehicle's diagnostic interface.

(l) Allowing sub-units of the ESS to be isolated for ease and safety of operation and maintenance.

(m) Locating the ESS so it does not obstruct any activities related to train operation.

(n) Locating the ESS so it does not impact the performance of equipment such as horns or alarms.

(o) Integrating human factors and ergonomics into the ESS design process.

3.1.5 Design principles for managing hazardous materials

Design controls for managing human interaction with hazardous materials of the ESS should include, but are not limited to the following:

(a) Implementing safe-handling procedures for all hazardous materials associated with the ESS throughout its entire lifecycle, including installation, operation, maintenance, storage, transport and disposal.

(b) Provisions for adequate ventilation and dilution systems to prevent the accumulation of flammable or hazardous gases and to minimize the risk of explosion in the event of a release.

(c) Inclusion of maintenance manuals that include all relevant safety data sheets (SDSs) for hazardous materials used within the ESS, ensuring that these documents readily accessible to maintenance personnel and emergency responders.

(d) The use of approved materials and substances throughout the ESS lifecycle, ensuring compatibility, safety and compliance with applicable standards and regulatory requirements.

Design documentation and the technical maintenance plan shall include information on all consumables so that only approved materials and substances are used throughout the life of the ESS.

3.1.6 Design principles for fire and explosion

The ESS shall be designed, installed and maintained to minimize the likelihood and consequences of overheating, fire and explosion.

Fire-safety provisions shall address detection, suppression, containment, emergency response and compliance with applicable Australian standards and recognized battery-safety frameworks.

The ESS shall incorporate fire-detection measures appropriate to the technology, installation environment and foreseeable failure modes. Detection systems shall:

(a) identify early indicators of thermal runaway, including abnormal temperature rise, off-gassing, smoke or rapid voltage changes;

(b) provide alarms to the driver, maintenance personnel and vehicle control systems;

(c) interface with vehicle-level safety systems to support automated protective actions; and

(d) be designed and installed in accordance with relevant Australian standards, where applicable.

Detection methods can include:

(e) temperature sensors at cell, module and pack level;

(f) gas or vapour sensors for electrolyte decomposition products;

(g) smoke detection within ESS enclosures; and

(h) BMS-integrated diagnostic algorithms.

The ESS shall include fire-suppression measures appropriate to the battery chemistry and installation environment. Suppression systems shall:

(i) limit the spread of fire within the ESS enclosure;

(j) prevent escalation to adjacent modules or vehicle systems;

(k) support safe evacuation and emergency response; and

(l) be compatible with the ESS materials and not introduce additional hazards.

Suppression strategies can include the following:

(m) Fixed suppression systems such as aerosol, water mist or inert gas.

(n) Thermal barriers or fire-resistant insulation.

(o) Automatic or manual activation mechanisms.

Where suppression systems are installed, they shall be accessible for inspection and servicing throughout the ESS lifecycle.

The ESS shall be designed to contain fire and thermal-runaway events to prevent propagation and protect vehicle occupants and critical systems. Containment measures shall include:

(p) module-level isolation to prevent cascading failure;

(q) fire-resistant enclosures or compartmentalisation to limit heat transfer;

(r) venting pathways to safely direct gases away from personnel and ignition sources; and

(s) structural design to withstand internal pressure rise during a thermal event.

Containment design should consider:

(t) worst-case thermal-runaway scenarios;

(u) environmental conditions typical of Australian operations; and

(v) requirements from relevant battery-safety frameworks.

The ESS shall incorporate measures to prevent hazardous temperatures on external surfaces and within compartments. These measures shall:

(w) prevent external surfaces from reaching temperatures that could cause burns during normal operation or foreseeable failure modes;

(x) ensure compartment temperatures remain safe for personnel performing routine tasks; and

(y) include insulation, shielding, ventilation or active cooling as required.

These requirements should apply to:

(z) normal operation;

(aa) high-load conditions;

(bb) thermal-runaway events; and

(cc) post-incident cooling periods.

The ESS shall support safe and effective emergency response through:

(dd) remote isolation capability from the driver's cabin;

(ee) clearly labelled emergency shut-off points accessible to responders;

(ff) integration with vehicle-level emergency procedures; and

(gg) provision of emergency response information consistent with australian whs regulations and sds requirements.

Emergency procedures shall address:

(hh) thermal-runaway response;

(ii) fire suppression and containment;

(jj) post-incident cooling and monitoring; and

(kk) safe handling of damaged or compromised ess components.

To prevent explosion hazards arising from gas release, the ESS installation shall include the following:

(ll) Adequate ventilation to disperse flammable or hazardous gases.

(mm) Dilution strategies to prevent accumulation above lower explosive limits.

(nn) Venting pathways that direct gases away from personnel and ignition sources.

(oo) Compliance with relevant electrical installation requirements where applicable.

ESSs can contain materials that are flammable and require robust risk mitigations. The ESS and its implementation shall comply with AS 7529.1:2020

3.1.7 Design principles for the handling of the ESS

Design principles for managing the handling of ESSs should include, but are not limited to the following:

(a) The location of the ESS through-life, including the multiple positions it can be in during the installation, maintenance and disposal processes.

(a) Using handling approaches and equipment that protect the ESS and can withstand the weight of the ESS to hold it securely during the installation, storage, transportation, maintenance and disposal processes.

(b) The location of other equipment and personnel relative to the ESS through-life and minimizing the possibility of dropping the ESS to harm people or dropping objects on the ESS.

(c) Securing the ESS to the vehicle structure using mountings that can withstand the static and dynamic loads that are expected to be experienced through life, including collision.

(d) Providing secure and adequately rated lifting points to interface with lifting equipment.

(e) Providing a visual indication of the equipment's centre of gravity.

(f) Providing protection against damage caused by weather events such as hail, falling tree branches or the ingress of dust/dirt/liquid, such as from flooding.

3.1.8 Design principles for construction

Design principles for ESS construction should include:

(a) a risk assessment process to ensure that the hazards at each step during construction are identified and safely managed in design;

(b) the ease of construction, including how the ESS interfaces are managed through-life;

(c) the standardization of parts, design for access of components and design for easy and safe movement of the ESS and its component.

(d) modular construction techniques to support factory acceptance testing and simplify field integration;

(e) provision for alignment features, lifting points and mechanical guides to reduce manual handling risks and improve repeatability;

(f) design for minimal rework or modification during installation (e.g., pre-assembled harnesses, plug-and-play connectors);

(g) the layout and routing of the main power bus, cabling and, where applicable, cooling and fire suppression systems, to ensure safe integration, accessibility and maintainability through-life; and

(h) provision for isolation at the battery level, including the design and placement of isolation devices to enable safe disconnection of individual battery modules or strings during construction, testing or maintenance.

3.1.9 Design principles for installation

Design principles for ESS installation should include:

(a) a structured risk-assessment process to identify, assess and control hazards associated with ESS construction, installation and integration activities;

(b) ease of installation to support safe and efficient installation into the vehicle including clear methods of handling, lifting and manoeuvring the ESS into position;

(c) the use of special tooling where required for the safe installation, removal or adjustment of the ESS; and

(d) ease of access to provide safe and convenient access to all required interfaces within the ESS.

Installation shall be conducted in accordance with the ESS manufacturer's instructions, and in accordance with design principles. Criteria shall be identified for the transport and storage of ESS prior to installation.

Refer to IEC 61881-3:2012 for installation guidance for EDLCs regarding overstressing, the cooling of connectors and parallel/series connection.

Refer to IEC 62928:2018 for guidance on the handling, storage and transport of batteries.

3.1.10 Design principles for maintenance

Design principles for maintenance should include:

(a) a risk assessment process to ensure that the hazards during maintenance are identified and managed safely in design;

(b) the ease of maintenance, including how the ESS and its subsystems are to be handled and moved into position;

(c) the ease of access to the required interfaces to safely perform maintenance activities;

(d) the use of special tooling that is used to maintain the ESS;

(e) the cost of the maintenance approach against the reliability, availability and maintainability of the ESS through-life;

(f) provisions for replacement components to maintain the performance and safety of the ESS throughout its design life, without introducing a requirement for functional modification;

(g) processes for covering exposed terminals to ensure that the risk of electric shock to workers is managed;

(h) provision for isolation at the sub-unit or module level to enable safe inspection, testing or replacement without requiring full ESS discharge or removal; and

(i) provision of diagnostic interfaces to support fault identification, performance monitoring and/or maintenance planning.

The design of the ESS should allow for the replacement of consumables, such as fuses and the accessibility of fuses and the likelihood of their current limits being exceeded.
If an ESU comprises of multiple sub-units that are difficult to access for maintenance, one level of fusing at the outer-most, most accessible level of the ESU should be used.

The design approach for consumable components such as fuses should include:

(a) the overall safety requirements;

(b) ease of access;

(c) the frequency of replacement;

(d) the availability of the system; and

(e) the potential for inadvertent or accidental incorrect component selection and misuse.

3.1.11 Design principles for disposal

Design principles for disposal should include:

(a) a risk-assessment process to ensure that the hazards during disposal are identified and managed;

(b) minimizing the amount of hazardous material during disposal;

(c) the ease of access to the required interfaces;

(d) the ease of repurposing or disassembly to recover materials; and

(e) adopting opportunities to minimize waste and gain value from the disposal approach.

3.2 Through-life assessment factors

3.2.1 General

Through-life assessment of the ESS shall assess all factors that influence safety, performance, reliability, maintainability and compliance throughout the entire lifecycle of the system.

Through-life assessment factors of the ESS should include:

(a) the design and engineering integrity of the system;

(b) the manufacturing quality and traceability of the ESS;

(c) installation, integration and compatibility with vehicle electrical, mechanical and thermal systems;

(d) the safety performance of the ESS;

(e) energy and power characteristics of the ESS against the operational requirements;

(f) availability, reliability and maintainability, including local technical support from manufacturers;

(g) the identification and control of hazards such as thermal runaway, fire, explosion and electric shock;

(h) influence on vehicle or railway availability, efficiency and performance;

(i) suitability for the operational context such as the natural and induced environment;

(j) ease of installation, commissioning, operation, maintenance and disposal;

(k) certification and compliance;

(l) the service life of the ESS;

(m) any training requirements for personnel involved in ESS lifecycle phases; and

(n) the total cost through-life.

Approaches to assess factors should include:

(o) review of documentation by an expert panel;

(p) inspection;

(q) modelling; and

(r) tests and trials.

See Appendix I for further information regarding the assessment, evaluation and implementation approach to the ESS.

3.2.2 Review of documentation by expert panel

A review of ESS-related documentation should be conducted to evaluate the factors of interest and determine whether the ESS meets the required safety, performance and compliance expectations.

Factors of interest can be assessed through a review of the available documentation. This type of review should be performed by:

(a) defining the factors to be assessed;

(b) gathering a person, or a panel, who is/are competent to make judgements on the factors of interest;

(c) defining the criteria for the assessment, for example what attracts a given score, rank or a pass/fail result;

(d) gathering documented evidence from stakeholders, such as manufacturers or testing institutions; and

(e) reviewing the evidence and allocating a result, referencing key evidence that justifies that finding.

3.2.3 Inspection

Factors of interest should be assessed by inspecting physical equipment or software.

This type of review should be performed by:

(a) defining the factors to be assessed;

(b) gathering a person, or a panel, who is/are competent to make judgements on the factors of interest;

(c) defining the criteria for the assessment, for example what attracts a given score, or a pass/fail result;

(d) inspecting the physical equipment or software, gathering evidence for justification, for example, consisting of notes, inspection data, photos and videos; and

(e) reviewing the evidence and allocating a result, referencing key evidence that justifies that finding.

3.2.4 Modelling

Analysis should be undertaken to understand the requirements and performance assessment criteria of ESS. Simulation software used for full and advanced analysis should validate and model the behaviour of the longitudinal train dynamics (as evidenced by peer review in technical publications).

The supplier of the longitudinal train dynamics simulation software should be able to provide evidence of its validation and suitability for its application to train dynamics studies.

A validation process should be followed for vehicle dynamic models that require individual vehicle dynamic simulations in addition to overall train simulations.

For reference, refer to *International Benchmarking of Longitudinal Train Dynamics Simulators: Benchmarking Questions* (2017, Vehicle System Dynamics, 55(4), Taylor & Francis, London).

Commentary *C3.2.4*

Power transients such as accelerating a vehicle from a standing start on a hill while overcoming friction provides the highest peak power demand on the traction motors, and therefore the supply from the ESS.

See Appendix D for information to determine ESS performance through modelling and analysis.

3.3 Operational requirements for energy and power performance

When developing the energy and power requirements for the ESS, the following factors should be taken into account:

(a) The type of train the ESS-fitted vehicle will be part of, for example light passenger rail or freight, understanding that heavier vehicles are likely to require larger energy storage capacity and higher powers.

(b) The potential applications and purpose, as well as the performance requirements on the vehicle for factors such as gradient, range, speed and acceleration through-life.

(c) The intended design life of the ESS.

(d) The variability or uncertainty in performance requirements and the variability in the delivered ESS performance.

(e) The efficiencies of the traction system, such as any converter and transformer efficiencies, the motor efficiency and the rolling losses.

(f) The method by which the ESS will be charged and discharged and the operating cycle for these events. If the ESU is charged infrequently, then a larger energy store could be required to sustain its function to the next charging event.

(g) The potential rate of charge of the ESS, such as from OHW or diesel electric power pack via the DC link or from regenerative braking.

(h) The safe limits on the rate of charge and discharge of the ESU, and the limits which prevent harm to the ESS or connected electrical equipment.

(i) The power transients that the traction system place on the ESS, both for demand and supply of power.

(j) The demand from auxiliary systems such as heating, ventilation and air-conditions, include variation within the operational environment, such as increased temperatures while operational.

(k) Degradation in power and energy performance throughout the ESS lifecycle.

(l) The energy demand from vehicle systems and their priority.

Energy storage and power thresholds shall be determined for the various routes where the vehicle will operate. Battery degradation should be monitored, so the replacement of the ESS or deployment of the vehicle to other services can be planned before the battery reaches the threshold condition.

Service planning should include procedures for operating with a degraded battery so that energy use is prioritized to allow finishing a journey or traveling to a point where recovery is possible.

Commentary *C3.3-1*

The key parameters of interest for the ESS are allowable charge and discharge rates, and the useful energy stored. ESS power application and purpose could be described in terms of operating profiles for how the vehicle will be used showing power variation in time. These are used with other traction system parameters to define the ESS power output and energy storage requirement.

Commentary *C3.3-2*

ESS performance could vary against expected requirements, for example, if the ESS power requirements were to be 5% above the nominal power target, and the manufactured ESU could have a 5% shortfall from the specification, then specify an ESS with 10% higher power than the nominal power target. Efficiencies of the traction system could vary within the operational environment, such as increased temperatures while operational.

Commentary *C3.3-3*

If a fault occurs in the PPS or the ESS, the graceful performance degradation profile could allow priority systems to operate for a set amount of time and capability.

3.4 Interoperability

Interoperability requirements placed on the vehicle shall be identified, decomposed and allocated to the appropriate systems across the vehicle architecture, including the ESS. The ESS shall be designed and implemented in a manner that enables the vehicle to meet all applicable interoperability requirements.

This includes ensuring that:

(a) vehicle-level requirements are systematically decomposed into subsystem-level requirements, with clear traceability to the ESS where relevant;

(b) interfaces between the ESS and other vehicle systems (i.e. electrical, mechanical, thermal, control, communication and safety systems) are defined, controlled and verified;

(c) the ESS supports all operational modes required for vehicle interoperability, including charging, propulsion, regenerative braking, auxiliary power and interaction with off-board systems;

(d) the ESS does not introduce constraints or incompatibilities that would prevent the vehicle from meeting regulatory, operational or performance obligations; and

(e) interoperability considerations extend through the lifecycle, including installation, maintenance, upgrades and end-of-life processes.

ESS implementations shall be set up to interface with the systems on and off the vehicle, as necessary for the vehicle to meet its requirements. In turn, the ESS can place requirements on other systems.

For principles of interoperability at the vehicle level for the Australian railway industry, refer AS 7450:2013

See Appendix E for further information on the interoperability aspects of ESS.

3.5 Environment

3.5.1 Naturally occurring environment

The ESS shall be suitable for the range of environmental conditions that can be reasonably be expected to be experienced through-life, as identified in the chosen approach to inform ESS selection. Naturally occurring changes within the environment should be taken into account when determining an appropriate ESS specification to meet operational needs.

The naturally occurring environment can refer to aspects such as temperature, humidity, altitude, rain, ice, snow, hail, lightning, air movement and solar radiation.

Depending on the intended locations of the ESS, it can be appropriate for an implemented ESS to be able to operate in a range of environmental conditions.

The ESS shall be protected from physical damage caused by weather events such as hail.

Refer to the CSIRO and Bureau of Meteorology, Climate Change in Australia website for more information. Available at: http://www.climatechangeinaustralia.gov.au

3.5.2 Induced environment

The induced environment refers to the ESS environment other than that which occurs naturally. The ESS should be assessed for a range of induced environments including:

(a) the chemical environment;
(b) biological environment;
(c) pollution;
(d) vibration and shocks;
(e) elevated temperatures;
(f) explosion risk;
(g) oxygen depletion due to enclosure or restricted ventilation;
(h) fire protection systems;
(i) electromagnetic environment; and
(j) acoustic noise environment.

The installed ESS shall be compliant with IEC 62864-1:2016

3.5.3 Unusual service conditions

Unusual service conditions can include those outside a naturally occurring environment and induced environment. Criteria shall be defined that establishes the unusual service conditions for the installed ESS through life. Refer to IEC 61881-3:2012 for further information.

3.6 Rail vehicle certification and compliance

The ESS and its implementation shall be designed, installed and commissioned in a manner that supports the certification of the rolling stock for compliance.

The following factors should be observed during the certification process:

(a) Alignment of all ESS related design decisions to the safety, performance and interoperability expectations defined in relevant standards.

(b) Installation and integration activities are carried out in accordance with recognized engineering practices and documented so they can be assessed during certification.

(c) Commissioning processes verify that the ESS performs as intended within the vehicle and that all safety and functional requirements are met.

(d) The evidence required for certification such as design artefacts, test results, hazard analyses and verification records is produced, traceable and available for review.

(e) The interfaces between the ESS and other vehicle systems support the vehicle's ability to meet AS 7501:2019 requirements without introducing non-compliances.

3.7 Testing

Testing for all ESS should be performed in accordance with IEC 62864-1:2016 which provides guidance on the categories of tests, the items to be tested, the system level and locations for tests. Testing can be performed as type tests, optional tests or routine tests.

Testing for ESS using batteries should be performed in accordance with IEC 62928:2018

Testing for ESS using EDLCs should be performed in accordance with IEC 61881-3:2012

Testing of the ESS to support compliance and the overall implementation strategy should be performed in accordance with EN 50215:2008

Commentary *C3.7*

Testing provides confidence in the performance, safety, reliability and suitability of an implemented ESS. The result of testing can support rail vehicle certification and compliance.

If retrofitting an ESS significantly changes the centre of gravity or load distribution, the effect on dynamics shall be assessed. In the case of significant change, tests shall be conducted to verify that dynamic performance is not affected. Refer to AS 7509:2017 for further information.

3.8 Maintenance

Maintenance shall include aspects such as inspection, testing, removal, repair and replacement.

Prior to commencing maintenance activities, the following should apply:

(a) Isolate the ESS from all external electric connectors on both polarities.

(b) Isolate the components of the ESS that are accessed for maintenance.

(c) Restrict access to authorized personnel.

Maintenance shall be conducted in accordance with the ESS manufacturer's instructions in accordance with the design principles. Each of the ESS components should be able to be serviced and maintained separately and independently. Any ESS components that require specialized servicing shall be removed on site and returned to the OEM for any repairs.

Maintenance procedures for testing, removal, replacement and servicing shall comply with the characteristics of energy storage unit (ESU) technology in accordance with UL 9540A:2025

3.9 Disposal

Disposal refers to the activities performed at the end of the ESS's operational life. Disposal shall be completed in accordance with the ESS manufacturer's instructions and the design principles. Disposal can occur when the ESS reaches its design life, becomes unsafe or when it fails to meet acceptable performance thresholds. Causes arise from damage or from repeated use.

Disposal options should include:

(a) disassembly and recycling of the material where possible;

(b) returning the ESS to the manufacturer; and

(c) repurposing of the ESS for other functions, such as wayside energy storage.

The disposal should be performed in accordance with an environmental management system that is compliant with ISO 14001:2015 so that it follows best practice.

Section 4 Safety

4.1 General

All hazards and risks associated with the integration of the ESS into vehicles shall be identified, assessed and managed for the ESS's intended application and operating environment throughout its entire lifecycle. This includes design, manufacture, installation, operation, maintenance, modification and end-of-life processes.

Risk-management activities shall be systematic, evidence-based and aligned with recognized safety-engineering practices.

Risk assessments and mitigation measures shall be documented at all stages of the ESS lifecycle to support:

(a) independent audits;

(b) engineering reviews;

(c) certification activities;

(d) change-management processes; and

(e) ongoing safety assurance.

Documentation should include:

(f) hazard identification records;

(g) risk assessments (qualitative or quantitative as appropriate);

(h) mitigation strategies and design controls;

(i) verification and validation evidence;

(j) residual-risk justifications; and

(k) change-impact assessments for modifications or upgrades.

Records shall be maintained in a controlled and traceable manner to ensure that the risk-management process remains transparent, repeatable and reviewable over the life of the ESS.

4.2 ESS integration hazards

ESS integration hazards and risks shall be systematically identified and assessed using a through-life, systems-engineering approach. The assessment shall consider all factors that might influence safety, performance and reliability throughout the ESS lifecycle. Hazards shall be identified and assessed at each stage of the ESS lifecycle, including:

(a) concept and design;

(b) manufacture and assembly;

(c) transport and storage;

(d) installation and integration with the vehicle;

(e) operation and maintenance;

(f) modification or upgrade

(g) decommissioning, removal and disposal.

The assessment shall consider the full range of environmental conditions the ESS and vehicle will experience, including the following:

(h) Natural environments (temperature extremes, humidity, dust, vibration, corrosion, weather events).

(i) Induced environments (electromagnetic interference, mechanical shock, operational loads, contaminants).

Hazards shall be evaluated in the context of the specific rolling stock types into which the ESS will be integrated, recognising differences in:

(j) duty cycles;

(k) operational profiles;

(l) physical constraints;

(m) system architectures; and

(n) Australian-specific environmental factors where relevant.

The assessment shall identify all personnel who might be exposed to ESS related hazards, including:

(o) drivers and operators;

(p) maintenance staff;

(q) emergency responders;

(r) passengers (where relevant); and

(s) bystanders or third parties during installation or recovery.

The types of energy or materials that could cause harm shall be identified, such as:

(t) electrical energy (high voltage, high current);

(u) thermal energy (heat generation, thermal runaway);

(v) chemical hazards (electrolytes, off-gassing, fire by-products); and

(w) mechanical energy (mass, inertia, crush hazards).

All systems interfacing with the ESS shall be identified and assessed for potential hazards arising from:

(x) electrical interfaces (power, control, communication);

(y) thermal interfaces (cooling systems, ventilation);

(z) mechanical interfaces (mounting, structural integration); and

(aa) software and control-system interactions.

The total amount of energy stored, transferred, or managed within the ESS shall be considered as a key hazard factor, including:

(bb) maximum stored energy;

(cc) peak power capability;

(dd) energy release during fault conditions; and

(ee) energy pathways during normal and abnormal operation.

NOTE 1:

For ESS safety requirements including electrical hazards, fire behaviour and protection, protection against impact and short circuit protection, refer to IEC 62864-1

NOTE 2:

For EDLC safety requirements, including discharge devices, case connections, environmental protection and other requirements, refer to IEC 61881-3

NOTE 3:

For battery safety requirements including markings, isolation for maintenance/service and fire protection, refer to IEC 62928

4.3 Safety case

A safety case shall be developed and maintained for each ESS implementation. The safety case shall provide a structured, evidence-based demonstration that the ESS, its integration into the vehicle, and its intended operation meet all applicable safety requirements throughout the system's lifecycle.

The scope and depth of the safety case shall be proportional to the risk posed by the ESS based on factors such as the following:

(a) Total energy capacity.

(b) Chemical composition and fire/explosion risk.

(c) Integration complexity and operational criticality.

(d) Proximity to personnel or hazardous materials.

(e) Environmental exposure and induced conditions.

(f) The novelty of the design.

The safety case shall:

(g) define the safety objectives relevant to the ESS and its integration with rolling stock;

(h) identify and justify all safety requirements, including those derived from hazards, standards and operational needs;

(i) present the results of hazard identification, risk assessment and risk-control activities, demonstrating that risks have been reduced so far as is reasonably practicable;

(j) provide traceable evidence from design, testing, analysis, verification, validation and operational data to support all safety claims;

(k) address interfaces between the ESS and other vehicle systems, ensuring that integration does not introduce uncontrolled hazards;

(l) demonstrate compliance with relevant standards, operator requirements and regulatory obligations; and

(m) be maintained through the lifecycle, updated when design changes, operational experience or new hazards emerge.

A complete safety case can provide an independent review, support certification and provide confidence that the ESS can be safely operated within its intended environment.

4.4 Collision and crash worthiness

Impact or puncture to the ESS can lead to damage, which in turn can lead to explosion, gas venting/release and other effects. All collision hazards and risks shall be identified and assessed.

Risk mitigation for collisions should include, but are not limited to:

(a) installation of the ESS away from potential crumple zones;

(b) implementing ESS design methods to protect the ESU components from impact;

(c) designing the structure of the ESS and vehicle interfaces to be strong and flexible enough to withstand the loads and control the deflections during a collision;

(d) prevention measures to mitigate fire, explosion and the venting or release of gases resulting from a collision, derailment or rollover;

(e) locating the ESS away from doors, windows and other emergency egress locations such as designated cut-out locations on vehicle roofs;

(f) isolating and containing harmful materials and energized components; and

(g) attach the ESS to vehicle components so that it can withstand the level of shock and vibration encountered in service.

For general guidance of rolling stock structure, rolling stock types, fatigue and verification, refer to AS 7520

4.5 Electric shock and short circuit protection

The ESS shall be designed, integrated and maintained to prevent electric shock and short-circuit hazards throughout all stages of its lifecycle. Protective measures shall ensure the safety of personnel, passengers and equipment during normal operation, foreseeable misuse, fault conditions and emergency scenarios.

The ESS shall incorporate measures to prevent electric shock arising from direct or indirect contact with hazardous voltages. These measures shall include:

(a) the use of physical barriers and enclosures and electric isolation devices;

(b) the earthing of the ESS casing;

(a) surge protection and fusing, to maintain safety to ESS personnel and the vehicle systems and protect against electrical transients, including lightning strikes;

(b) implementing the ESS with lockable isolators or a lockable bypass switch where it is connected to the DC link, with clear visible indicators as to the isolators state;

(c) allocation of appropriate PPE to personnel;

(d) the use of indicators to the state of charge or fault status of the ESS;

(e) the use of cables and connectors that comply with AS 7530:2018;

(f) removal of mechanical wear on cables and connectors, where it could cause other components to become live from damage;

(g) maintaining the ESS in accordance with the manufacturer’s instructions;

(h) maintaining electrical cables and connections so they continue to comply with AS 7530:2018;

(i) the use of suitable methods for the discharge of the ESS to a lower energy state;

(j) designing the ESS with appropriate internal component clearances and creepage distances so that elevated dirt/dust/moisture ingress due to cooling/air filtration failure or neglect does not result in risk of an electric shock or a thermal event;

(k) implementing physical security measures such as locks, so that only those permitted to access the ESS can do so;

(l) implement markings to indicate the location of the ESS and the electrical shock hazard it presents to personnel;

(m) isolating/separating high voltage components from other components and clearly marking them;

(n) segregating and isolating energy storage components within the ESU to minimize the amount of electrical energy that can be released;

(o) minimising the contact between ESS and other electrically live systems; and

(p) providing a local indication of the safe state of the ESS for operation and maintenance personnel.

The ESS and its implementation shall comply with AS 7530:2018 or an equivalent standard such as EN 50153

See Appendix F for information regarding short circuit protection.

4.6 Thermal runaway, fire and explosion

4.6.1 Thermal runaway

All hazards and risks that could contribute to thermal runaway shall be systematically identified and assessed throughout the ESS lifecycle. This process shall consider the full range of factors that could initiate, accelerate or exacerbate thermal-runaway events, including design, manufacturing, integration, operational, environmental and maintenance-related contributors.

The assessment shall:

(a) identify all credible initiating events that could lead to thermal runaway (e.g., electrical, thermal, mechanical, chemical, or software-related).

(b) evaluate the likelihood and consequence of each hazard in the context of the intended vehicle application and operating environment.

(c) consider interactions between ESS subsystems and interfacing vehicle systems that could influence thermal stability.

(d) assess degradation mechanisms, ageing effects and through-life changes that could increase susceptibility to thermal runaway.

(e) include foreseeable misuse, abnormal operating conditions and fault scenarios.

(f) document all identified hazards, associated risks and mitigation measures to support traceability, audits and safety-case evidence.

This requirement ensures that thermal-runaway risks are understood, controlled and demonstrably managed so far as is reasonably practicable across the entire ESS lifecycle.

The ESS and its implementation should comply with IEC 60077-1:2017 or equivalent.

See Appendix G for a list of risk mitigation measures for thermal events and electric shock.

4.6.2 External ignition sources

If an ESS is to be provided on a vehicle which also carries flammable or explosive materials, such as diesel fuel, the ESU shall be placed at a safe distance from the fuel tank. Both the tank and the ESS containment structure shall be designed to minimize any possibility of fire, including in a collision or derailment.

Risk mitigation measures for external ignition sources should include, but are not limited to the following:

(a) Containing the heat, fire and explosion completely within the ESU enclosure.

(b) Placing the ESU a safe distance away from such materials.

(c) Limiting the use of the ESS-fitted vehicle to haulage operations that will not expose the ESS to such materials.

(d) Designing the vessels of materials that will contain heat, fire and explosion.

4.6.3 Emergency response

Emergency-response risk-mitigation measures shall be implemented to ensure that incidents involving the ESS such as electrical faults, thermal events, toxic releases or mechanical damage can be managed safely and effectively. These measures shall protect passengers, personnel, emergency responders and the surrounding environment.

Risk mitigation measures for emergency response should include the following:

(a) Onboard systems to extinguish fires.

(b) Markings to indicate the location of the ESS and the hazard it presents to response personnel such as danger of explosion and danger of electric shock.

(c) Reducing the amount of hazardous material in the ESS.

(d) How the extinguishing substance (e.g., water) can reach the ESS if pumped from outside of the vehicle. This includes when the vehicle is rolled over, such as from collision or derailment scenarios.

(e) Readily accessible PPE for emergency response personnel and the location and availability of the PPE.

(f) The response time and resources available from emergency services to respond to an ESS incident.

RTOs should refer to their emergency management/response plans to ensure the safe and effective management of ESS thermal runaway, fire or explosion emergency events.

4.7 Toxic and corrosive material

The ESS can contain materials that are toxic, corrosive or otherwise hazardous to human health and the environment. All hazards and risks associated with these materials shall be identified, assessed and controlled throughout the ESS lifecycle, including design, manufacture, transport, installation, operation, maintenance and end-of-life processes.

The use of toxic or corrosive materials should be avoided in the construction of ESSs as materials can become toxic once they are spilled or burned during fire. Toxic materials associated with ESS technologies can include battery electrolytes, off-gassing products and fire by-products.

Risk mitigation measures for managing toxic and corrosive materials should include, but are not limited to:

(a) limiting the amount of toxic and corrosive material within the ESS;

(b) limiting the amount of material in the ESS that becomes toxic and corrosive on exposure to heat or fire;

(c) reducing the risk of excessive heating;

(d) providing controlled routes for gaseous and liquid material to either be contained or diverted away from the ESS to a safe location; and

(e) implementing ingress protection to contain harmful dust, dirt or liquid within the ESS.

4.8 Component and release at velocity and fluid release at pressure

All hazards and risks arising from components being released at velocity, and high-pressure fluid release shall be identified and assessed.

Components of the ESS can be released at high speed if they are not restrained against the loading acting on them. Tension, compression, pressure and torsional loading can all cause solid components to become detached from their mountings and any remaining elastic energy can be converted to kinetic energy.

Risk mitigation measures for managing the release of components at velocity and high pressure fluid release should include, but are not limited to:

(a) following OEM design guides for the attachment of the ESS to the vehicle structure;

(b) containing the ESS components within a structurally sound casing to contain components should they become detached during loading;

(c) designing components of the ESS to be strong enough to withstand the pressure foreseen through life;

(d) maintaining the ESS, its mountings, venting and pipework through-life; and

(e) installing the ESS in accordance with manufacturer's instructions.

4.9 Dynamic stability

Dynamic stability of an ESS can be influenced by a range of electrical, thermal, mechanical, software and integration-related factors. These risks shall be identified, assessed and controlled to ensure the ESS maintains stable performance during normal operation, transient events and fault conditions.

Risk mitigation measures for managing the dynamic stability of ESSs should include:

(a) installing the ESS at, or below, the centre of gravity of the rest of the vehicle;

(b) installing the ESS so that its centre of gravity is on the lateral centreline of the vehicle, so that no one side of the vehicle is more likely to overturn than another;

(c) performing dynamic numerical modelling of the vehicle with the ESS, within the operational context; and

(d) the impact of sloshing loads if the ESS contains liquid.

4.10 Structural

The integration of an ESS into rolling stock introduces additional mechanical loads, dynamic forces and environmental stresses that can affect the structural integrity of both the ESS and the host vehicle. All risks that could contribute to structural failure shall be identified, assessed and controlled throughout the ESS lifecycle.

ESS can be heavy and place additional weight and dynamic loads onto rolling stock structures and bogies causing structural failure due to overloading.

Risk mitigation measures for managing structural failures due the implementation of the ESS should include, but are not limited to the following:

(a) Using a structure and mountings that can withstand the predicted dynamic and static loads for the ESS implementation, when applying load reserve factors to those loads.

(b) Using suspension and bogies that are strong enough for the ESS implementation.

(c) Performing dynamic structural modelling of the interaction between the ESS structure and the rail vehicle to verify structural performance.

(d) The impact of free surface effects if the ESS contains liquid.

(e) Attaching ESS equipment to vehicle bodies that are designed to withstand the level of shock and vibration encountered in service.

ESS shall be designed to safely withstand the shock and vibration environment through-life.

To prevent physical damage caused by shock and vibration the following steps should be taken:

(a) Design the shock and vibration response of the structural interface between the ESS.

(b) Design the shock and vibration response of the ESS internal components.

(c) Monitor the change in the shock and vibration response through time due to degradation of components.

4.11 Electromagnetic compatibility (EMC)

The ESS can influence the electromagnetic environment of the rolling stock and its surrounding systems through emissions, coupling effects and susceptibility to external electromagnetic sources. All risks that could adversely affect electromagnetic compatibility shall be identified, assessed and controlled to ensure that the ESS does not compromise the performance, safety or reliability of the vehicle or nearby systems.

The ESS implementation shall allow the ESS to operate as intended in the through-life electromagnetic environment.

The ESS implementation shall not adversely affect the electromagnetic environment so that other vehicle equipment can operate as intended.

The ESS implementation shall be in accordance with AS 7722:2026 or equivalent.

Electromagnetic interference can be mitigated by using electromagnetic shielding around sources of interference.

4.12 Functional failure

Functional failure of the ESS can arise from a wide range of technical, environmental, operational and integration-related factors. All risks of functional failure shall be identified, assessed and controlled to ensure the ESS performs reliably throughout its lifecycle and within the intended rolling-stock environment.

ESS functional failure can be caused through:

(a) the system not functioning at all;

(b) the system functioning outside of specification, such as outputting the wrong amount of energy or power compared to what is required by the system; and

(c) the degraded ESS function such as atypical environmental conditions or the failure of a cell or capacitor within the ESS.

Shore supply and traction circuit shall be interlocked so that traction cannot be applied when the shore supply is connected to charge the ESS.

4.13 Software and cybersecurity

The ESS can introduce cybersecurity risks due to its reliance on electronic control systems, communication interfaces and software-based safety functions. Software that is critical to the safe operation of the ESS can interface with a number of third parties and be exposed to a potential cyberattack.

Cybersecurity risks shall be identified, assessed and managed to ensure that cyberthreats cannot compromise the safety, reliability, or performance of the ESS or the rolling stock in which it is integrated.

The configuration control, management and maintenance of ESS software shall be monitored to protect safety critical functionalities from potential cybersecurity breaches.

Appendix A Hazard Register (Informative)

Hazard number	Hazard
2.1.10	The failure to identify and document major hazards across operations
2.1.27	The failure to maintain and service equipment, infrastructure and rolling stock
3.2	A breach of Security
3.2.1.30	Arson
3.2.1.34	Cyber attack
3.2.1.35	Sabotage
5.32	Fire
5.3.1.39	Harmful exposure to noise
5.38	Hazardous substances contact
5.4.1.38	EMI
5.42	Electric shock - Failure of protection
5.3.1.9	Large mass, shape or size of objects when manual handling
5.3.1.15	Sharp edges, burrs or cuts
5.3.1.46	Poor posture
5.14	Alerting system failure
5.20.1.3	Complicated, continuous cognitive functioning being required to operate trains
5.20.1.4	Continual interruptions / messages from onboard systems
5.17.1.9	The view from seating positions being affected by cab structures and / or equipment (Seating position affecting vision)
5.43	Explosion
5.2.1.8	Objects dropping down / falling off trains causing collision with wayside structures
5.29.1.14	Mounts or components failing due to fatigue (Rolling stock equipment - Object drops down / falls off a train)
5.29.1.16	Mount fasteners not being tightened properly (Rolling stock equipment - Object drops down / falls off a train)
Clause	Description
5.3.1.13	The environment being too cold causing thermal stress
5.3.1.14	The environment being too hot causing thermal stress
5.3.1.31	Hot equipment causing burns by conduction
5.20.1.10	Uncomfortable temperature
5.3.1.43	Harmful exposure to released pressured gas or fluid

Hazard number	Hazard
5.4.1.62	Inadequate rolling stock modification
5.6.1.6	Brakes being applied somewhere on train and traction not cutting out resulting in uncommanded traction
5.8	Collision
5.19.1.44	Vehicles overturning
5.19.1.45	Vehicles overturning due to loading to one side causing vehicle unbalance/wheel unloading/overturning
5.28.1.2	High centres of gravity
5.28.1.7	Liquid load moving to one side (Load off to one side)
5.28.1.8	Loads being inadequately restrained (Load off to one side)
5.28.1.9	Poor loading (Load off to one side)
5.28.1.6	Overspeed (Overturning at higher speeds to outside of curve)
5.29.1.14	Mounts/components failing due to fatigue (object drops down/falls off a train)
5.31	Out of gauge trains
5.34.1.7	Devices obscured by fixtures resulting in horns/beepers not being loud enough
5.37.1.14	Poor quality water - Contaminated source
5.37.1.9	Surfaces inadequately cleaned creating contaminated surfaces
5.40.1.9	Crushed between wheel and rail during inspection/maintenance
5.25.1.14	Overloaded rolling stock (frame cracking or bending – frame failure)
5.25.1.15	Overloaded rolling stock (spring failure – suspension failure)
5.44	Bodily impact
5.45	Evacuation hazards
5.46.1.10	Traction system faults (excessive longitudinal acceleration)
5.53	Inadequate vehicle assessments
6.7	Inadequate Rail Safety Worker Competencies
—	Thermal runaway caused by overvoltage or overpowering ESS components, leading to fire
—	Thermal runaway caused by mechanical damage to the ESS from impact or stressing of the ESS, leading to fire
—	Thermal runaway caused by excessive temperature in operating environment, and the ESS not being cooled, leading to fire
—	Thermal runaway caused by overvoltage or overpowering ESS components, leading to explosion

Hazard number	Hazard
—	Thermal runaway caused by mechanical damage to the ESS from impact or stressing of the ESS, leading to explosion
—	Thermal runaway caused by excessive temperature in operating environment, and the ESS not being cooled, leading to explosion

Appendix B System and Subsystem Levels (Informative)

IEC 62864-1:2106 provides the relationship between the standards in terms of levels of systems and subsystems. These systems are as follows:

(a) Level 1 is the vehicle/system interface.

(b) Level 2 is system and interfaces.

(c) Level 3 is components.

(d) Level 4 is subcomponents.

The following provides a summary of the content of these standards and the additional guidance:

(a) IEC 62864-1:2016 for power supply with onboard energy storage system covers basic system electrical configuration, tests to verify and some guidelines for manufacturing and evaluating. It is defined as Level 1/2, or across the vehicle/system interface and system levels. This Standard builds on IEC 62864-1:2016, by providing further guidance that considers the Australian rail operational context to inform:

    (i) the performance requirements, design guidance throughout the ESS lifecycle; and

    (ii) the identification and mitigation of relevant safety hazards.

(b) IEC 61881-3:2012 for electric double-layer capacitors (EDLC) is at the component level (Level 4) within the IEC standard structure. It focusses on the quality requirements and testing of EDLCs. It provides guidance to support their design, selection and use, including their installation and operation. This Standard builds on IEC 61881-3:2012 by providing further guidance that considers the Australian rail operational context to inform:

    (iii) the performance requirements and design guidance throughout the ESS lifecycle; and

    (iv) the identification and mitigation of relevant safety hazards.

(c) IEC 62928:2017 for lithium-ion batteries is at the component level (Level 4) within the IEC standard structure and discusses the design, operation, parameters, safety recommendations, data exchange, routine and type tests as well as marking and designation. It includes broad coverage of operational conditions as well as some guidance in using the operational pattern for sizing. This Standard builds on IEC 62928:2017 by providing further safety guidance related to the Australian rail operational context.

Appendix C Rolling Stock Electrical System Configurations (Informative)

C.1 General

IEC 62864-1:2016 provides an overview of some possible electrical system configurations including an ESS, where the ESS comprises of the following electrical components:

(a) An energy storage unit (ESU).

(b) A converter to convert the ESU output voltage to that required for the vehicle.

(c) An ESS bypass switch within the system boundary.

The component of key interest within the ESS is the ESU due to the novelty of large-scale batteries and EDLCs and the severity of the hazards they cause. The ESU consists of one or multiple components that repeatedly store and release electrical energy in a controlled manner. ESU component technologies other than batteries and EDLCs are out of the scope of this document as per Clause 1.2

The ESU is likely to have a power level that is of the same order of magnitude as the power of the traction system. This can vary significantly from vehicle to vehicle depending on the purpose of the train, ranging from light rail through to freight. The ESU is likely to store energy to provide the functions described in Clause 2.1 for a useful period before recharging, which range from seconds to hours based on the implementation and operation.

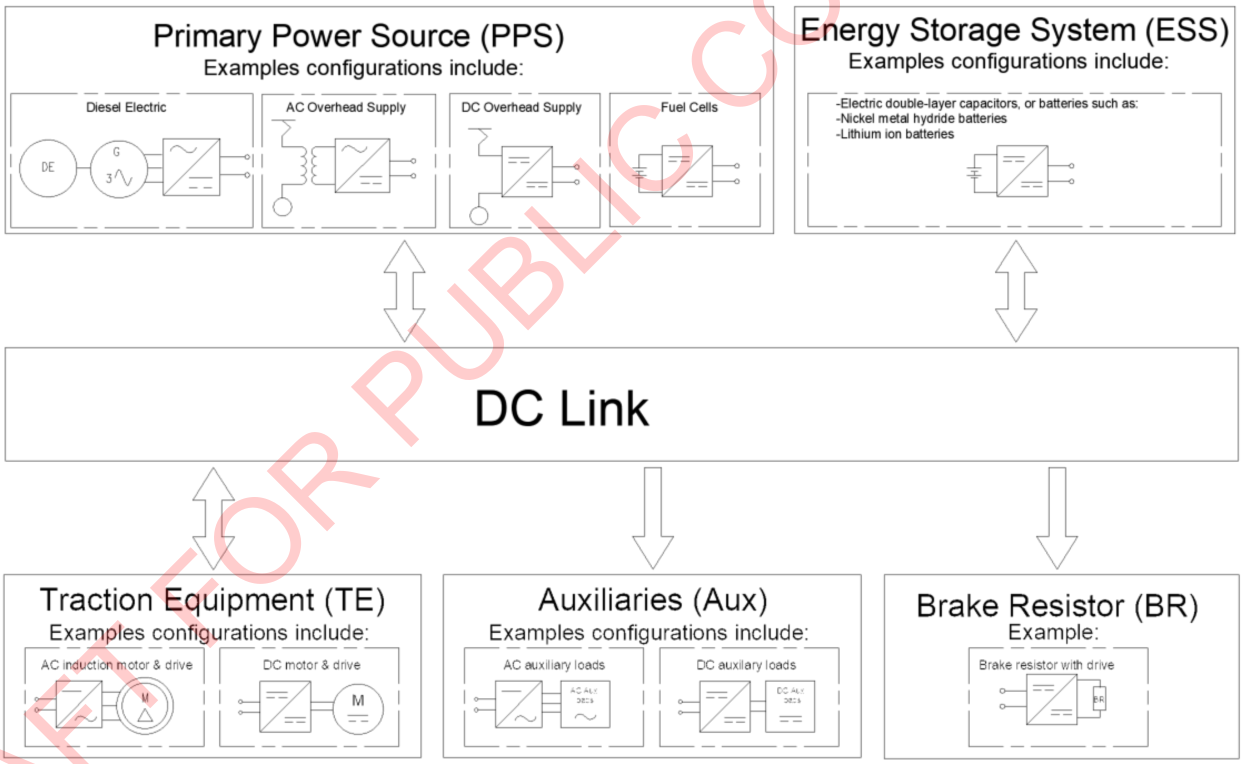

Figure 1 Typical rolling stock electrical system configurations including an ESS

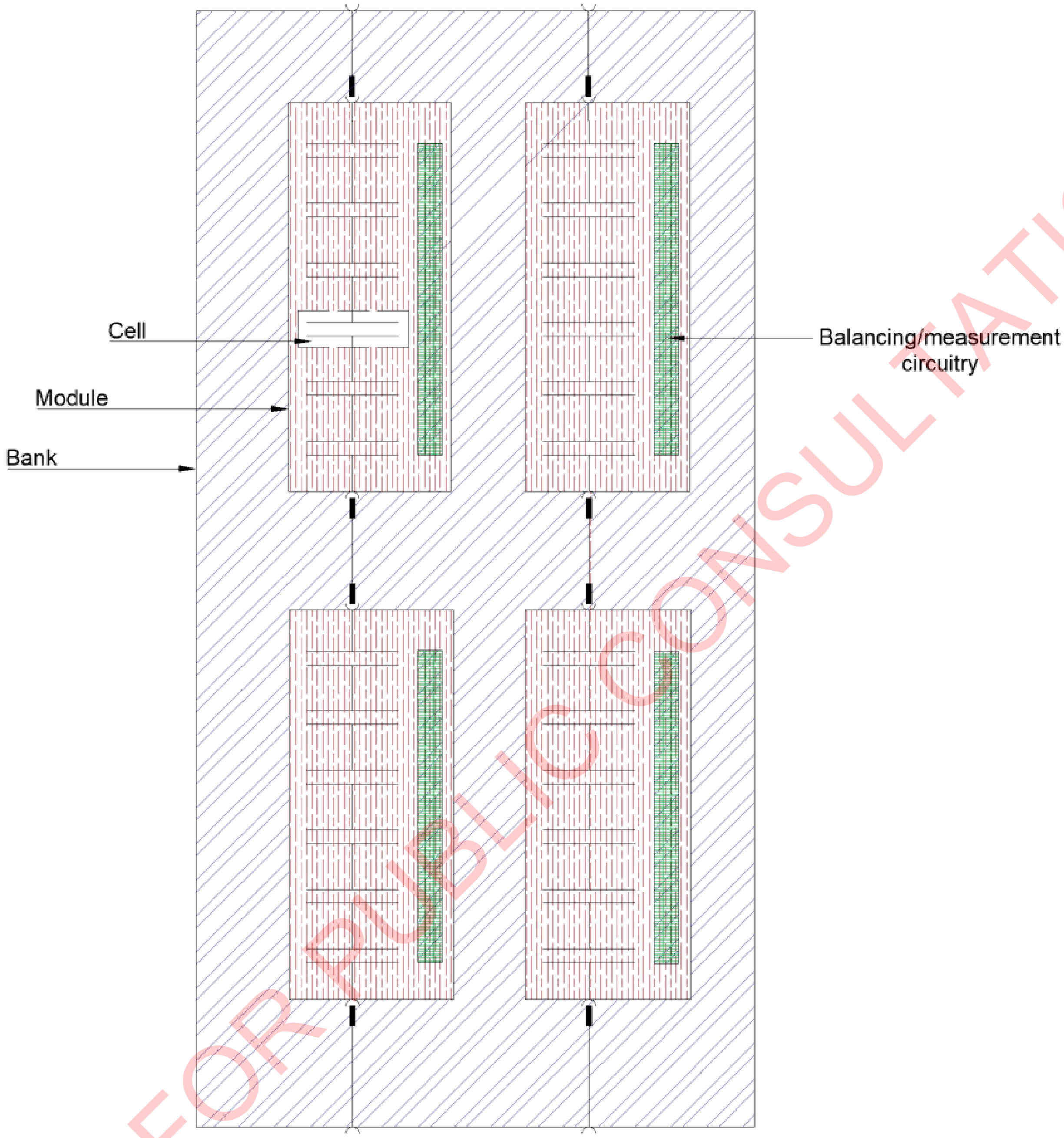

Figure 2 Block diagram of a series hybrid system

Figure 2 shows ESSs to include the battery system as the ESU, and comprises of a battery converter, inductor, switchgear and cooling system. Within the battery system there is a battery management system (BMS), which include a battery thermal management system (BTMS).

IEC 62928:2017 Section 4 provides further information on the configuration of battery systems.

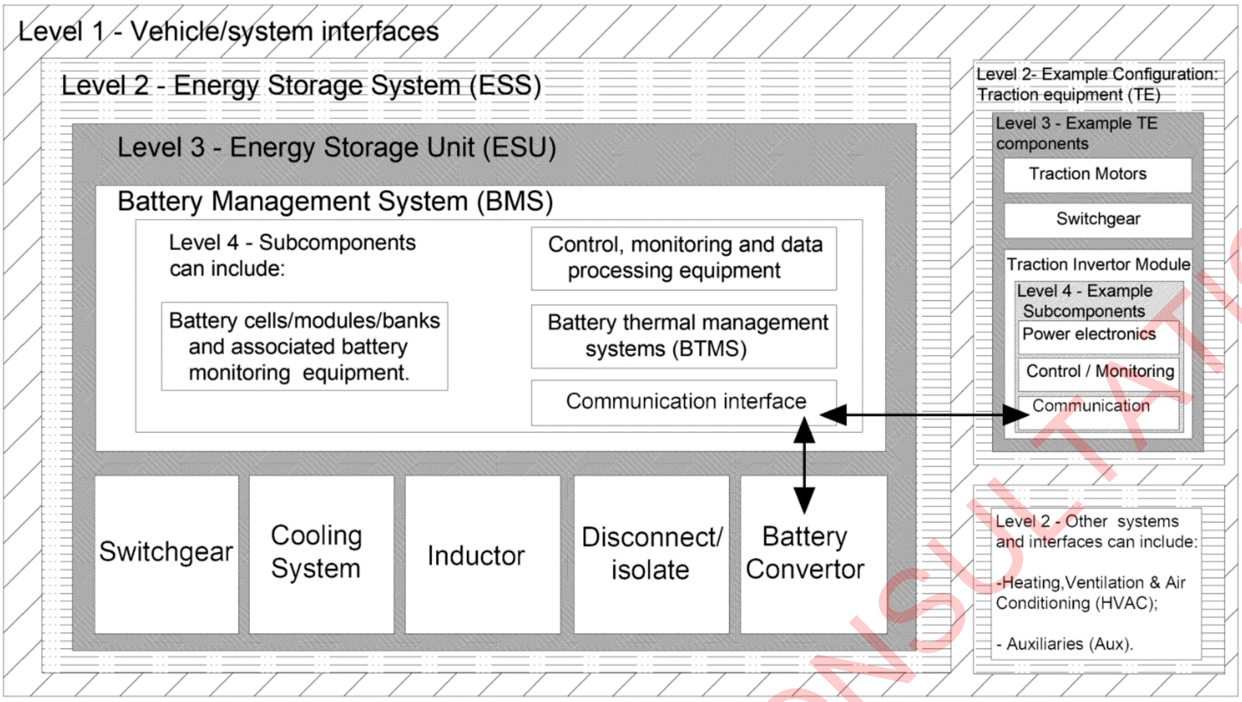

Figure 3 Block diagram of a battery ESS

C.2 Systems interfacing with the ESS

The ESS interfaces with the following systems, through the interfaces described below:

(a) Train control & management system (TCMS): The overall protection and control system, or systems, for the vehicle. The interface with the TCMS takes the form of connectors and cables carrying electrical control signals comprising of either analogue voltages/currents from sensors, or logical signals to communicate data.

(b) Vehicle electrical systems: The ESS is connected to the DC link as illustrated in IEC 62684-1:2016 Section 4 and illustrated in **Error! Reference source not found.**. The DC link is the main traction power connection between the PPS (onboard power generation or external traction electrical supply through a current collection device) and the traction equipment including the dynamic brake converter. Other loads powered by the PPS such as the auxiliary power supply system is connected to the DC link. The ESS provides power to the DC link for the traction equipment and will be recharged using power from the DC link from the PPS and or from the traction equipment during electrodynamic braking. As power flow is often controlled by power electronics an isolating switch is included at the interface between the ESS and the DC link for safety.

(c) Offboard electrical systems: The ESS directly connects to offboard electrical systems without connection to the vehicle DC link. An offboard DC connection distributes power between the ESS to offboard the vehicle. This is most likely to be accomplished via a physical shore supply receptacle on the vehicle, or by wireless transfer of power.

(d) Cooling system: The ESS includes an internal cooling system to take heat away from the internal subsystems and components to the boundary of the ESS. An additional cooling system, through an active fluid interface, is used to remove waste heat from the ESS boundary, such as a heat exchanger, if the environment for the ESS does not provide sufficient passive cooling.

(e) Vehicle structure: The system which reacts to loads to hold vehicle components in position. The interfaces are the mechanical fixings such as bolts, rivets, spigots and anti-vibration mounts to hold the ESS to the structure in position, withstand loads, balance loads across the vehicle and manage shock and vibration.

(f) Safety systems: The ESS is supported by external safety systems which includes isolators, extinguishers, smoke extraction and venting. The ESS is either connected to these systems, or independent from them. For example, the ESS will provide temperature signals to the TCMS to operate an external extinguishing system, or alternatively an independent sensor connected solely to the TCMS detects high temperatures and operate the extinguishing system. A fluid interface is used to enable venting from the ESS. Gas generated from the ESS needs to be vented during operation or in response to high temperature or pressure.

(g) Installation systems: Systems that are used to install and commission the ESS onto the vehicle.

(h) Maintenance systems: Systems that are used to maintain the ESS.

(i) Disposal systems: Systems that are used to dispose of the ESS.

Appendix D Modelling and Analysis to Determine ESS Performance (Informative)

The following provides a summary of the level of analysis that could be taken to understand the requirements and performance assessment criteria of ESS:

(a) Simple analysis: this analysis is limited to a quasi-static case and does not fully represent the actual ESS performance for train operational scenarios. However, it allows the estimation of the minimum energy required for a trip by assuming an average main speed and computing the sum of the resistances to motion, and the potential energy effects resulting from changes in altitude.
The energy usage is also subject to signalling conditions; braking, stop-starts and the design of grades, this is addressed within the simple analysis. For reference, refer to *Design and Simulation of Rail Vehicles* (Cole, 2014) and the study *Longitudinal Heavy Haul Train Simulations and Energy Analysis for Typical Australian Track Routes* (Cole et al., 2014).

(b) Full analysis: this analysis considers the longitudinal behaviour of the train as a function of many issues including train control inputs from the locomotive, train brake inputs, track design characteristics and vehicle connection characteristics. Vehicle mass, passenger load, HVAC load and regenerative braking are also included.
In this analysis, the battery behaviour and performance is described with simplistic equations and algorithms that represent the outcomes of ESS management strategies for actual train configurations running on the specific track section. For reference, consult the article *Conceptual Designs of Hybrid Locomotives for Application as Heavy Haul Trains on Typical Track Lines* (Sun et al., 2013, Proceedings of the IMechE Part F, 227(5), pp. 439–452).

(c) Advanced analysis: this type of analysis presents additional extensions to the full analysis that focus on the interaction of longitudinal train dynamics and rail vehicle full mechatronic models, and it is performed in a sequential or co-simulation mode in/between longitudinal train dynamics simulators, multibody software packages and a graphical programming environment or similar software products for simulating and analysing a full multidisciplinary system using system engineering approaches.

    (i) Development and analysis of battery or capacitor element behaviour at the individual or package levels.

    (ii) Detailed analysis of the ESS power system and its management algorithms (e.g. detailed element characteristics, power integration strategies, heat transfer and cooling processes etc.).

    (iii) ESS management strategies for rail vehicle or train operational scenarios.

For reference, refer to *Rail Vehicle Mechatronics* (Spiryagin et al., 2021, CRC Press, Boca Raton, FL).

Appendix E Interoperability Factors (Informative)

E.1 Interoperability – Vehicle to vehicle

If a vehicle is predicted to produce unacceptable in-train forces, then the specification of the tractive power curve for the vehicle's traction system, including the response of the ESS, is likely to be influenced. For ESS fitted vehicles this arise due to:

(a) ESS fitted vehicles that have a different tractive power curve that impacts when inserted in a train consist using distributed power; and

(b) ESS fitted vehicles that are configured to increase the efficiency of a passenger or freight train consist that also uses power cars or locomotives not fitted with ESS. In this operating mode, an efficiency strategy requires the braking effort to be mostly undertaken by the ESS fitted vehicle to maximize regenerative braking energy capture and storage.

Another example of a requirement placed on the vehicle is the definition of how it is required to interface with the electrical network, if at all. The system requirements placed on the ESS address the decomposition of vehicle requirements across electrical requirements. The vehicle requirements could require engagement with rail infrastructure managers (RIM) and network operators.

E.2 Interoperability – Between rail networks

Difference characteristics between railway networks that could influence ESS implementation includes the following factors:

(a) Gauge: The kinematic envelope of the vehicle and the position of the ESS across gauges.

(b) Voltage and power quality: Identify whether the operation of the DC link changes between networks and therefore whether the ESS operation is also required to change.

(c) Supply chain: Are the components to enable the ESS through-life available in all regions of interest.

(d) Support and maintenance capability: Are the systems to support the ESS available in all regions of interest.

(e) Network operations philosophy: How the ESS is used or limited in its use under network policy.

(f) Software: How ESS software is compatible with the local interfacing control systems.

Appendix F Short Circuit Information (Informative)

Test requirements to test internal short-circuits protections at the component or cell level are specified in IEC 62619:2022 for lithium batteries. Internal short-circuit protection could cause internal fuses to permanently isolate shorted individual or groups of battery cells from the rest of the battery.

Internal short-circuits could result from intrinsic causes such as cell failure or extrinsic causes such as physical damage to battery cell including penetration with a sharp conductive object. By isolating the shorted cell or groups of cells, thermal runaway is prevented and function preserved at the cost of a small voltage drop.

Test requirements to test external short circuits protections at a system level are specified in IEC 62928:2016 for lithium-ion traction batteries. System level external short-circuit protection use ancillary external fuses and contactors to disconnect the energy storage system. This short-circuits protection protects against short-circuiting of the battery box output.

IEC 62928:2016 Annex A shows examples of ESS configurations including the location of the contactors and battery management system in relation to battery box that contain the individual ESU battery packs or modules.

The contactors or circuit breakers and battery management system could be internal to and part of the battery box or external to the battery box.

The configuration with the internally located contactors is used to prevent the exposed battery box terminals from being live during storage and handling. The internal contactors/circuit breaker are only cut in by the control system or safety systems once the battery box has been installed and all safety systems activated. If this configuration is used, the isolation system will be interlocked with the internal contactors.

On those systems with both OHW and shore supply connections, an interlock will be incorporated to ensure that the OHW is restrained from being connected to the train with the shore supply connected.

The length of the unprotected cable or connection between the fuse or contactors and the batteries is generally kept to a minimum.

Appendix G Thermal Event Mitigation Measures (Informative)

Thermal runaway can be caused by electrical damage, short circuit (internal, external), overcharging, excessive currents while charging/discharging, mechanical damage, overheating, manufacturing defect, sabotage or arson.

ESUs are energy dense and in failure modes or damaged conditions can rapidly release large amounts of energy that result in thermal runaway, fires and explosions.

Lithium-ion batteries can present enhanced fire risk due to the largely flammable components of the battery that releases oxygen during a fire making extinguishing by smothering with water or other fire retardant difficult.

ESS that use batteries can be susceptible to thermal runaway, leading to high temperatures, fire and potentially explosions. Thermal runaway describes the process where the battery components are heated leading to a reaction which in turn can create more heat.

Thermal event mitigations include, but are not limited to the following:

(a) Preventing the ESS from being damaged either through electrical or mechanical means.

(b) Installing the ESS such that the temperature of its environment, both natural and induced, are within the acceptable limits of the design as communicated by the manufacturer.

(c) Ensuring segregation to external ignition sources such as fuel.

(d) The use of fire resistant casing materials and coatings for the ESS, such as using intumescent paint. This can reduce the hazard caused by arson.

(e) Provide local and remote overtemperature and fire alarms to notify operations and maintenance personnel.

(f) Design the ESS and its mounting to be able to expand and contract under heating, cooling and pressurisation.

(g) Design the ESS so that any surfaces that could be touched by people are at a safe temperature during normal operation during thermal runaway.

(h) Perform routine inspections and maintenance to verify the integrity and operation of the ESS as instructed by the manufacturer.

(i) Allow for any gas within the ESS to safely vent and disperse away from the vehicle, reducing pressure in the ESS and dispersing flammable gas away from sources of ignition.

(j) Protect the ESS components and any thermal management systems from harmful ingress by dust, dirt or liquid which could lead to build ups of flammable material or will prevent cooling/air filtration systems from working as intended.

(k) Implement the ESS in a structure that contains or restrains projectiles and that mitigates explosions. The methods of mitigating the explosions such as frangible panels or deflagration venting will reduce the risk and control the release of pressure rather than the structure suffering a catastrophic failure.

(l) Identify methods for venting the force of an explosion, including low frequency explosive force, or methods to contain projectiles.

(m) Use smoke exhausting systems.

(n) Provide sufficient cooling to the ESS to cover expected environmental extremes and faults in the cooling system. This includes variations in environmental pressure.

(o) Provide extinguishing systems using the correct extinguishing medium for the ESS and its installed location.

(p) Use ESS with internal extinguishing capability.

(q) Use an ESS management system that monitors voltage, potential faults, state of charge and temperature and responds appropriately.

(r) Prevent overcharging of the ESS by managing the connection to the DC link and severing it when necessary.

(s) Preventing arc flash within and around the ESS.

(t) Preventing water accumulation and condensation in the ESS.

Appendix H Assessment for ESS Selection and Implementation (Informative)

H.1 Assessment to inform ESS selection and implementation

Assessments are conducted to evaluate a candidate ESS specification and implementation approach. Assessments can provide:

(a) confidence that the candidate ESS and implementation complies with the general design principles; and

(b) confidence as to which candidate ESS and implementation is the preferred option when alternatives are assessed.

The overall assessment process includes:

(c) determining the level of confidence needed in the overall assessment, for example high, medium and low; and

(d) determining the factors of interest and how important they are in the overall assessment.

Combining the results of individual factors assessments with their respective importance, to reach a final decision on the overall assessment. The level of certainty required in the assessment determines the rigour applied to the assessment approach. For higher levels of certainty assessment approaches include increased levels of rigour considering the repeatability, accuracy and uncertainty in the body of evidence underpinning the assessment.

Appendix I Energy and Power Operational Performance (Informative)

The following energy and power aspects are applicable when developing the ESS:

(a) The type of train the ESS-fitted vehicle will be part of, for example light passenger rail or freight, understanding that heavier vehicles are likely to need larger energy storage capacity and higher powers.

(b) The potential applications and purpose, as well as the performance requirements on the vehicle for factors such as gradient, range, speed and acceleration through-life.

(c) The intended design life of the ESS.

(d) The variability or uncertainty in performance requirements, and the variability in the delivered ESS performance.

(e) The efficiencies of the traction system, such as any converter and transformer efficiencies, the motor efficiency and the rolling losses.

(f) The method by which the ESS will be charged and discharged and the operating cycle for these events. If the ESU is charged infrequently, then a larger energy store could be required to sustain its function to the next charging event.

(g) The potential rate of charge of the ESS, such as from OHW or diesel electric power pack via the DC link or from regenerative braking.

(h) The safe limits on the rate of charge and discharge of the ESU, and the limits which prevent harm to the ESS or connected electrical equipment.

(i) The power transients that the traction system place on the ESS, both for demand and supply of power.

(j) The demand from auxiliary systems such as heating, ventilation and air-conditions, include variation within the operational environment, such as increased temperatures while operational.

(k) The demand from auxiliary systems for both normal and degraded operation (i.e. one or more ESU non-functional).

(l) Degradation in power and energy performance throughout the ESS lifecycle.

(m) The energy demand from vehicle systems and their priority.

The OEM instructions are to apply if the ESS goes below the minimum energy and power performance thresholds during asset life.

Bibliography (Informative)

- AS 7521:2018, Interior Crashworthiness
- AS 7770:2018, Rail Cyber Security
- EN 50121-3-2:2016, Railway applications – Electromagnetic compatibility – Part 3-2: Rolling stock – Apparatus
- EN 50126:2017, Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Part 1: Generic RAMS Process
- EN 50126:2017, Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Part 2: Systems Approach to Safety
- EN 50128:2020, Railway applications – Communication, signalling and processing systems – Software for railway control and protection systems
- EN 50153:2014, Rolling Stock – Protective Provisions relating to electrical hazards
- EN 50215:2009, Railway Applications – Rolling Stock – Testing of rolling stock on completion of construction and before entry into service
- IEC 61373:2010, Railway applications – Rolling stock equipment – Shock and vibration tests
- ISO 14001:2015, Environmental management systems – Requirements with guidance for use
- Cole, C. (2014) *Design and simulation of rail vehicles*. CRC Press, Boca Raton, FL.
- Cole, C., Spiryagin, M., Wu, Q. & Sun, Y. (2014) *Longitudinal heavy haul train simulations and energy analysis for typical Australian track routes, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 228(4), pp. 355–366.
- National Fire Protection Association (2018) NFPA 68: *Standard on explosion protection by deflagration venting*. Available at: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=68 (Accessed: [date]).
- National Fire Protection Association (2019) NFPA 69: *Standard on explosion prevention systems*. Available at: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=69 (Accessed: [date]).
- Spiryagin, M., Bruni, S., Bosomworth, C., Wolfs, P. & Cole, C. (2021) *Rail vehicle mechatronics*. CRC Press, Boca Raton, FL.
- Spiryagin, M., Wu, Q. & Cole, C. (2017) *International benchmarking of longitudinal train dynamics simulators: benchmarking questions*, Vehicle System Dynamics, 55(4), pp. 450–463.
- Sun, Y., Cole, C., Spiryagin, M., Godber, T., Hames, S. & Rasul, M. (2013) *Conceptual designs of hybrid locomotives for application as heavy haul trains on typical track lines', Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 227(5), pp. 439–452.

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