RISK MANAGEMENT OF ELECTRIC VEHICLE CHARGING ON FUEL FORECOURTS AND ENCLOSED CAR PARKS

Paper No. PCIC Europe EUR22_04

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Abstract – As the rapid adoption of electric vehicles (EV) across the globe increases, so does the need to charge these vehicles. Charging locations now include fuel forecourts and enclosed car parks, e.g., basements and multistorey car parks. Risks associated with a battery fire during charging have been poorly understood by the industry.
This paper will use the familiar industry bow tie analysis model for risk management as a framework to represent the preventative and mitigation barriers to manage the risk events. Relevant detail will be shared on each barrier.
The result will be a globally applicable process and tool to identify, manage and communicate risks related to electric vehicle charging in challenging locations.

Index Terms — Electric vehicle charging, risks, EV fires, lithium-ion, bow tie model, forecourts, enclosed car parks, safety, barriers.

I. INTRODUCTION

Factors to consider when charging an EV include location (open air, forecourts and enclosed areas) and charging speed. Open-air locations pose a lower risk in the event of an EV fire and will not be specifically referenced in this paper.

Fuel forecourts are increasingly being used as high power/ultra-fast charging locations as charging speeds aim to replicate the current hydrocarbon re-fuelling duration. (Charging power ranges from home charging: 7-20kW; destination: 50-70kW; fast: 100-200kW; ultra-fast >200kW. Hydrocarbon refuelling rates: ca. 300kWh/min)

With land being a key factor in identifying suitable charging locations, building basements and multistorey car parks appear attractive opportunities.

Both enclosed areas and forecourt locations present safety risks should a lithium-ion EV battery ignite. EV batteries are notoriously difficult to extinguish and can continue burning for days[1]. This differentiates risks between fires of internal combustion engine (ICE) vehicles and EVs.

Lithium-ion batteries fail due to mechanical, electrical and thermal abuse which may lead to cell thermal runaway and once ignited, may burn uncontrolled, producing intense local heat, noxious gasses and toxic contaminants.

For home charging cases, the density of charging EVs is less (1 or 2 EVs at any one location), and the charging rate is usually lower. The consequences are less (although dire for the homeowner), so whilst still carrying a safety risk, this scenario will not be considered specifically. Parallels do exist, and the risk mitigation proposed within this paper could be used.

The reader will be introduced to the bow tie analysis for risk management. This will serve as the framework to represent the preventative and mitigation barriers to manage the risk event(s). Pragmatic recommendations will be discussed for industry to develop, implement and verify the health of each barrier.

II. RISK AND THE BOW TIE MODEL

A. Risk

Risk is the product of consequence and impact. While a **hazard**, is something that can cause harm or result in a negative situation, a **risk** is the chance (likelihood, or probability - high or low), that any **hazard** will cause a negative outcome (risk event) and the consequences of that negative event. Identifying and mitigating the hazards in EV charging installations can be represented on a bow tie diagram.[2] See figure 1.

B. Barrier bow tie Model

Following the catastrophic Piper Alpha platform event in 1988, the Cullen report [16] concluded that there was insufficient understanding of hazards and their accompanying risks. Originally developed by Imperial Chemistry Industry (ICI) and further standardised and adopted by the Petrochemical industry, the bow tie model has gained support in industry as a visual tool, useful to assure that appropriate risk controls are implemented consistently.

The bow tie (figure 1) examines chains of events, or accident scenarios and then identifies control measures to prevent these events. The left-hand side of the bow tie uses a typical fault tree methodology (Boolean AND/OR gate) to model causal relationships between events, while the right-hand side utilises an event tree thinking. Using the Swiss Cheese model (James Reason ca. 1990's), the bow tie identifies control measures, known as barriers.

C. Barriers

Barriers are independent, mutually exclusive and able to prevent an event from occurring or escalating. Preventative barriers sit on the left-hand side and represent those control measures in place to prevent the cause from producing the risk event. Mitigation barriers are right hand side controls that prevent the risk event from escalating to the anticipated consequences. [2]

The Swiss Cheese metaphor considers that barriers are never 100% effective. At some stage, the deficiencies (holes in the cheese) in all the barriers along a causal path may fail (line up), resulting in the risk event from occurring (LHS Preventative barriers), or the risk event escalating to the Consequences (RHS, Mitigation barriers)

Unlike risk management techniques such as Fault Tree, layers of protection analysis (LOPA) or Risk graph, the bow tie method does not consider likelihood or frequency but rather if the controls are available, healthy and effective.

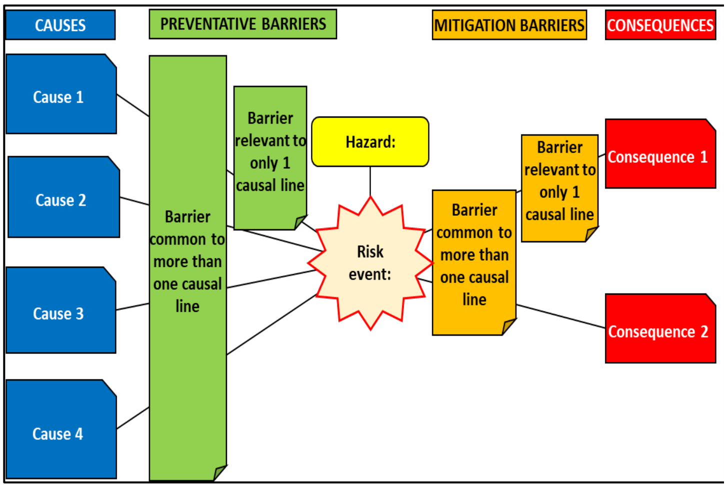

Figure 1 Bow tie risk assessment model

D. Determining if barriers are healthy.

Determining barrier effectiveness is a key factor when considering risk management. An ineffective barrier will not prevent the risk event from happening. Key questions to consider regarding barriers and risk are:

- What is the risk?
- What are the barriers?
- Who owns them?
- Do they work?
- How do you know?

Representing barrier health on a bow tie is a very useful visual tool for communicating a complex message to a wide audience.

III. EV CHARGING HAZARDS

Hazards involved in charging EV's include the use of electrical energy. When not controlled, this energy can become an ignition source or result in electrocution.

Hydrocarbon re-fuelling activities on forecourts create hazardous areas within which the use of non-rated electrical equipment is restricted.

The stored electrical energy within lithium-ion batteries is a hazard if the battery or control/safety system fails.

IV. EV CHARGING RISKS

The frequency of EV charging incidents is relatively low although the number of incidents may be increasing as rapid EV adoption occurs. Low likelihood, high consequence events do occur and as a responsible charge point operator (CPO), these need to be addressed.

The main two risk events related to EV charging are electrocution of personnel and fire from a failed lithium-ion battery.

A. Electrocution

Working on or near electrical equipment can pose a risk of electrocution. EV charger outputs range from 7kW home chargers to megawatt charging (trucks, busses). At these power levels, sites may require high voltage installations, transformers, low voltage switchgear and concomitant supporting infrastructure.

Installation, maintenance and operation activities can expose personnel to electrocution risks if these are not addressed appropriately.

Being mostly industrial standard equipment, the preventative and mitigation barriers around this equipment are well understood. Nevertheless, as the EV charging business escalates, so parties less well versed with applying the applicable safety standards are active and hence, electrocution risks remain a key contributor to overall site risks.

B. Fire

EVs are currently powered by Lithium-ion batteries. They are also used as energy storage systems in battery buffered high power charge points. Failures within cells can quickly lead to fire and explosion of adjacent cells. Uncontrolled thermal runaway follows.

Increasing reports of EV battery and Energy Storage System fires have led to vehicle and property destruction, injuries, and major EV recalls in the US, Europe, and Asia, e.g. Hyundai's recall of its Kona EV's earlier this year. In the Battery Energy Storage System (BESS) segment there have been 38 large BESS fires since 2018 and in July 2021 Tesla's 450 MWh Megapack project in Victoria, Australia caught fire, requiring 7 days and 150 firefighters to extinguish. 23 BESS fires in South Korea (2017 to 2019), resulting in losses valued at $32 million. A 2019 grid-scale battery storage system fire in Arizona caused extensive injuries and damage. High profile BESS fire incidents have affected insurers' risk tolerance. [3,4,5]

When discussing battery fires, it is useful to appreciate how EV batteries are constructed and their failure mechanisms.

1) Li-ion battery construction

An EV battery consists of multiple smaller cells that are constructed with an anode and cathode separated by a porous electronically insulating separator. (See Figure 2)

During discharge, lithium leaves the anode as lithium-ion (Li+) and an electron (e-). The Li+ flows through the ion conducting electrolyte and separator to the cathode. [1]

As the separator is electronically insulated, the electron must flow via an external circuit where useful work is done.

During re-charge, the Li+ ions and electrons on the anode recombine on the cathode to form lithium on the cathode electrode.

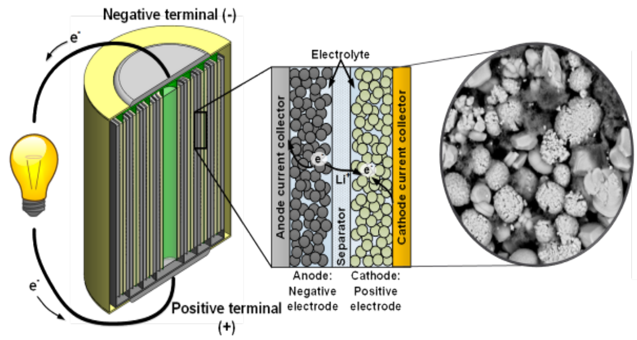

Figure 2. Li-ion battery construction and operation

The heavy EV batteries are usually located in the lower, central section of an EV within an enclosed casing of robust construction. Access is restricted and any firefighting opportunities are particularly challenging (figure 3).

Figure 3. Typical location and construction of EV battery pack. Batteries contained in the chassis base. *(Credit Autocar.co.uk)*

2) Li-ion battery failure modes – manufacturing defect

Contaminants in raw materials, damages during construction and the high number of cell components within a battery result in challenges in the defect detection during manufacturing. These defects are seldom identified during quality control, testing or operation. [17]

3) Li-ion battery failure modes – degradation [1,6]

Li-ion batteries can degrade over time or fail rapidly.

Degradation can be caused by high or low temperature, high current/loading, high or low voltage/state of charge per cell, number of cycles, chemical or mechanical stress.

The degradation mechanism includes growth or decomposition of the solid electrolyte interphase layer, lithium plating or dendrite formation piercing through the separator, and general failure of the battery component parts.

This leads to the loss of lithium inventory, active anode material or active cathode material and results in a capacity loss or power fade.

While degradation is usually a time related occurrence, accidents to EV or BESS batteries can result in a rapid deterioration, due to failure of the battery monitoring management system (control system).

4) Li-ion battery failure modes – rapid failure/accidents

Accidents related to lithium-ion battery failures can be caused by:

Mechanical abuse – deformation or separator tearing (e.g. crash, shock, crush or penetration).

Electrical abuse – internal short circuit, lithium dendrite growth leading to the piercing of the separator (e.g. internal short circuit, over discharge, over charge).

Thermal abuse – high temperature leading to a collapse of the separator (e.g. overheating).

All the above can result in an internal battery short circuit leading to thermal runaway.

This failure may occur in a single cell, but as these are closely packed within the EV or BESS, thermal runaway can quickly lead to flames, explosion, oxygen release, high temperature and a myriad of noxious gasses (hydrogen fluoride (HF), phosphorus pentafluoride (PF_5), hydrogen cyanide (HCN) and carbon monoxide (CO)) being released. Studies into the failure mechanisms of many battery types included the gaseous emissions and toxicity [1, 7, 8]

5) Identifying failures in Li-ion batteries

Li-ion battery failures are time dependent, however failure can occur rapidly after damage or abuse.

Consider the following failure detection options:

- Electrolyte vapour detection: The event in which the cell case vents due to a rise in internal pressure of the cell is termed off gas. (NFPA 855/UL 9540A). [6, 7] This unique event is useful to determine incipient faults within the battery construction. At the early stages of failure, lower explosion limit sensors or voltage, temperature and current measurement variations are not easily detected, as the characterises have not changed much. However, the electrochemical reaction inside the battery creates a noticeable amount of gas at this early stage. Some commercially available detectors use gas sensors to monitor and detect off gassing events a few seconds after failure occurs and long before battery measurements are effective. Early detection coupled with a correctly designed shutdown system is an effective safety barrier. Note, this method cannot predict the state of the battery.
- Measure terminal voltage variations using battery management system. This is a widely used monitoring method with redundancy and comparative measurements assumed to be providing integrity, but due to the complexity of programmable systems and a lack of segregation between control and protective safety systems this assumption may not result in the required integrity and is difficult to validate. This method is not very fast at identifying early stages of thermal runaway.
- Monitor the battery temperature using embedded fibre Bragg grating optical temperature sensors or electrochemical impedance spectroscopy measurements. This method provides an accurate temperature measurement but adds cost and complexity to battery packaging.
- Measure current variations (short circuits). The BMS can be configured to measure current flow. Any abnormal rate of current flow or load-requested level can trigger an alarm indicating a potential short circuit. Usually irreversible failure has occurred at this stage.
- Measure mechanical deformation or delamination of electrode coatings. Other than visual or x-rays, no commercially viable passive method is employed.

6) Li-ion battery fire management.

Internal short circuits consequences can be discussed in 3 levels as summarised in Table 1.

TABLE 1
BATTERY FAILURE CHARACTERISTICS.

Level	Cell voltage	Cell temperature	Identification and consequences
Level 1	At cell voltage, but slow decrease	Slow increase, self-discharge, no/low obvious heat	Off gas detection Electrical approach, BMS identification. Self-extinguish behaviour.
Level 2	Fast decrease	Rapid increase, Joule heating	Electrical-thermal coupled approach. Consequences depends on heat dissipation.
Level 3	No voltage	Thermal runaway. Joule + chemical reactions	Too late. Unstoppable consequence.

The temperature increases rapidly over time up to about 100°C, increases slowly further up to about 200°C after which the separator and electrolyte separating the anode and cathode fails leading to a significant rapid increase in temperature to well above 500°C. Figure 4 represents an example of different cathode materials.

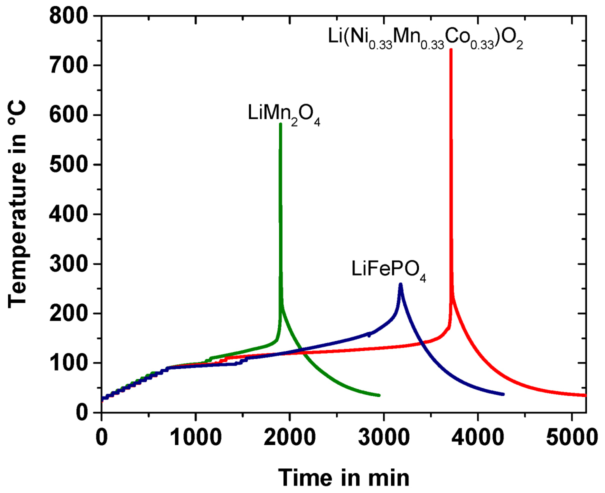

Figure 4 Typical temperature versus time of different cathode material failures [18]

As the heat from an internal cell fire and the resulting thermal runaway causes lithium to generate oxygen and react with water to form hydrogen, fire water only serves as a cooling mechanism rather than oxygen depletion. Cooling water can also act as a conduction medium between voltage containing parts of the failing battery or vehicle. As such, a Li-ion battery can burn and continue to burn for many days. This poses new and significant challenges to the fire services and affected parties and may have environmental consequences for the CPO.

Currently, the industry is generally inadequately prepared for Li-ion battery fire prevention and the resulting consequences.

7) Battery or BESS bow tie

While the bow tie concept will be discussed in the following sections, for completeness, Appendix A [13] offers a typical risk bowtie of a Lithium-ion cell failure in a typical battery of BESS system.

V. CAUSES OF EV CHARGING RISKS

While many activities can lead to an EV charging risk event happening, the causes can be combined into the following categories:

A. Working or operating on or near live electrical equipment

This includes human interaction with live electrical equipment, including batteries during installation, operating, maintenance as well as the public exposure to EVSE.

B. Operating above the safe design limits

This cause includes equipment being required to operate above design value or environment. This may be due to operator or user requirement or external factors affecting the equipment capability.

C. Failure of equipment

Whilst an obvious cause of a risk event, failure of the equipment can include all EVSE, the EV charger (EVC), cable, any component parts or the battery. It includes component parts of the equipment (e.g. insulation exposing live parts)

D. Ignition of battery or flammable fuels

The failure and subsequent ignition of a Li-ion battery will cause a risk event. Flammable fuels, e.g. a forecourt fuels spillage, will contribute to this risk event.

VI. CONSEQUENCES OF EV CHARGING RISKS

A. Injury, Electrocution or fatality

A credible consequence of a failure of the electrical equipment – be it equipment integrity, operation or any related activities, can vary from a mild electrical shock to electrocution and even a fatality. High power levels are in use by a wide range of personnel competencies.

B. Property or reputational damage and/or loss of business.

Any safety incident, or fire could result in damage to the operator's reputation or even in a closure of the site, or, if significant, the business itself. Whilst legally the Landlord or EV driver may be the responsible party, the CPO may face an unintended reputational risk.

Other minor consequences e.g. environmental impact, consequential escalation damage were considered and merged into the two mentioned above.

VII. APPLICATION OF THE BOW TIE MODEL TO EV CHARGING SITES

A. Basic bow tie model [2]

Representing the causes, risk event and consequences on a bow tie presents the model shown in Figure 5.

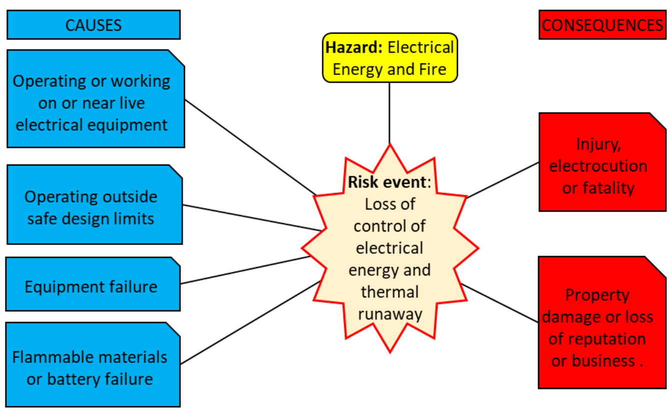

Figure 5. Bow tie model showing causes, risk events and consequences of EV charging hazards.

B. Barrier bow tie model

To prevent the risk event from happening, or to reduce the consequences of the risk event should it occur, we use barriers. Representing these on the bow tie offers the model shown in figure 6 (see Appendix B for a larger format.)

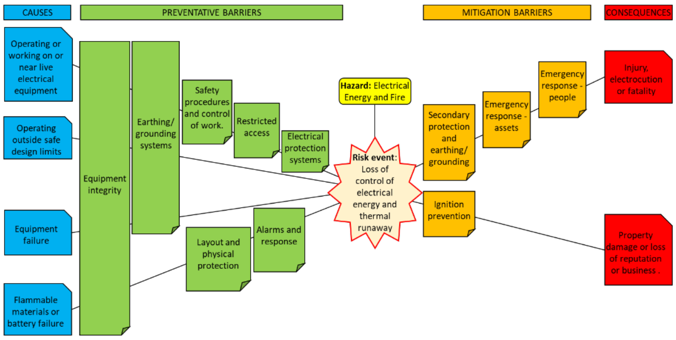

Figure 6. Barriers added to the bow tie model

C. *Interpreting the bow tie model*

To understand and apply the bow tie, it is useful to learn how to read the model.

A situation may have a hazard. In this case, we have combined two hazards for simplicity. These are electrical energy and fire.

Hazards result in a risk event. Loss of control of electrical energy and Fire are the highest risk events from the hazards identified.

A risk event is caused by a condition, action or threat. Combining causes results in the four listed in section V (Working on or near electrical equipment; operating above the safe design limits; failure of equipment and ignition of fuel or battery) Note, many other causes are possible. These are combined into credible causes without losing any content.

A risk event may result in a consequence. The possible consequences are electrocution or fatality, and damage to property or reputation. Essentially these are personnel and non-personnel consequences. Other minor consequences are possible but merged for clarity.

Barriers prevent or mitigate the risk event. They stop or reduce the "risk event from happening or getting worse".

Preventative barriers prevent the cause or threat causing the risk event from happening, i.e., they reduce the likelihood of the undesirable situation from happening.

Mitigation barriers minimise or limit the consequence of the risk event, after it has occurred, i.e., they stop things getting worse. They may also be labelled Recovery barriers.

Every barrier has control measures to determine the barrier health. Examples include maintenance, competence, standards, processes, tools, etc. These should not be seen as barriers in themselves, as maintenance, for example, will not prevent a faulty piece of equipment from electrocuting someone. It will however strengthen that barrier (e.g., equipment integrity) or a lack of a control measure (maintenance) will weaken a barrier. Often this is down to interpretation, but ultimately it is better to represent barriers as per their definition – independent and mutually exclusive.

Having interpreted the bow tie model, the real benefit lies in its application.

Barriers should be designed, tested, reviewed, assured or verified to determine their health or effectiveness. Barrier health can be represented as:

- In place, available and effective.
- In place, available with opportunities to improve.
- Not in place, not available, or not fully effective.
- Not tested or insufficient data available.

Representing these with various colours of choice, helps to create a graphical representation of the current risk profile of the site. If all barriers on a causal line are not in place, not available or not fully effective, then, per the Swiss Cheese model, one should expect the risk event to occur/escalate.

This simple model has been used across the globe to represent a myriad of risk events, ranging from health status, oil and gas operations, financial models, and many other scenarios. Exploiting proven tools across the wider industry benefits nascent businesses.

VIII. EV CHARGING RISKS BARRIERS

The core of this paper discusses each barrier and a list of recommendations to consider are offered to the reader.

These are based on experience and are not exhaustive. Some recommendations are based on international standards, or regulations and should be read as requirements, whilst others are recognised and generally accepted as good engineering practices.

A. *Preventative barriers* [9,10,11, 15]

1) *Equipment Integrity.*

a) *Site feasibility and design:*

Equipment integrity considerations should start at the initial site feasibility and appraisal stage.

Consider the location of equipment with respect to existing hazardous areas, fire risk (e.g., enclosed parking areas) and fire mitigation/extinguishment. [5]

A site check list which includes access, traffic flow, hazardous area considerations, electrical supply options and requirements, fire risk and mitigations, customer requirements, etc is useful.

Consider equipment size, weight (enclosed car parks may have a point load restriction (N/m^2)), access to maintain or operate.

Early-stage considerations can affect the type of equipment which in turn may affect its integrity.

b) *Design of EVSE:*

Apply international and local equipment standards which cover both AC and DC EVSE, battery energy storage, the plugs, sockets, cable connectors, vehicle inlets, and all associated supply equipment. (e.g., high voltage grid connection, HV/LV switchgear, transformer and associated equipment) and functional safety of control, protection and mitigation systems implemented using electrical/ electronic/ programmable electronic systems.

For forecourt designs, ensure designers are experienced in hazardous areas management and incorporate these into the design of the equipment and site.

For EVC cable management, consider cable abrasion, vehicle drive-over, DC insulation protection, electromagnetic compatibility risks, screened/shielded cables, cable management systems and return-to-holder management via human machine interface (HMI) or mobile application. Consider cable length with respect to vehicle parking practices, personal injuries (slips and trips) and access for disabled persons.

Inspection and maintenance activities include safety functions testing, diagnostics, electrical protection, cyber security and the management of ventilation of the EVC and EVSE. Consider dust, pollution, the local environment and the Original Equipment Manufacturer's recommendations and frequencies when creating an inspection and maintenance plan.

Consider the use of interconnected devices that perform functions with a high level of autonomy (smart devices) that can provide remote monitoring and control functionality. This can monitor equipment health status, condition monitoring and to receive and manage any alarms, trips and other communications. This is particularly useful when the CPO has many EV charging sites across a wide geography, Consider the increasing cyber security risks ranging from every payment to the whole CPO back-office operation.

Use physically separate, diverse and possibly redundant systems for control, protection and mitigation systems to reduce the likelihood of common failure.

EVC display screens can be configured to view and manage the equipment integrity. These include EVC diagnostics, charging statistics and battery integrity. Most algorithms include a cable and connection self-test prior to energisation, thereby managing the cable and connector integrity, charge stop or alerts to the operator can be configured within the HMI.

Consider EVC algorithms or handshake protocol logic that inhibit known EVs with poor batteries from being charged. ISO 15118 [12] supports vehicle to grid charging and in particular plug and charge – which addresses secure communication between EVs and EVCs, EVSE and the Utility grid.

Consider the source of manufacturing integrity of BESS batteries.

c) Off gas detection [6, 7, 8]

Consider gas detectors aimed to identify any incipient off-gas emissions from a failing battery. These may prove very useful as some manufactured products identify gaseous emissions many seconds before any significant voltage or thermal activity can be measured.

2) Earthing/ grounding and bonding

As pressurised systems in industrial plant use relief valves to mitigate overpressure situations, the electrical equivalent is a robust earthing system that sinks fault current into the mass of the earth. Ensuring that this barrier is effective is vital to prevent a causal path developing into a risk event.

Consider the type of earthing system to implement. Most countries require EV chargers to be TT earthed. (Terra- terra - direct earth connection). In the UK, the neutral and protective conductor may be combined after the HV/LV transformer secondary winding, resulting in a TN-C (Terra Neutral Combined system). A separated system (TN-S) is required for EV charging.

When high voltage equipment is required, consider the earth/ground potential rise (EPR) or (GPR). This occurs when a large current (e.g., fault current) flows to earth through an earth grid impedance. The potential is the highest at the point where current enters the ground and declines with distance from the source. The EPR around a substation may cause the voltage over distance (potential gradient) to be dangerously high between a person's two feet or between the ground on which the person is standing and a metal object. Any conducting object connected to the substation earth ground, such as re-fuelling equipment, rails, fences, or metallic piping, may also be energized at the ground potential of the substation. This transferred potential is a hazard to people and equipment outside the substation area.

Soil resistivity, underground metal objects and the distance between high and low voltage substations affect EPR. This may result in the HV and LV substations being up to 20 m apart. Many forecourts do not have this available space, resulting in the site being unsuitable for EV charging. Specialist software exists to calculate EPR and provides a complete earthing study (e.g., Current Distribution, Electromagnetic fields, Grounding and Soil Structure Analysis – CDEGS)

Lightning protection of the site should be considered for high-risk areas and included into the electrical design.

Extraneous bonding should comply with the earthing philosophy adopted.

3) Personnel and equipment electrical protection systems

A robust barrier of personnel and equipment protection is necessary to prevent uncontrolled electrical energy from harming people or equipment. Basic electrical protection against shock and faults provides automatic disconnection or separation of the supply.

Grading and protection studies are recommended to provide the correct discrimination. These should include thermal, over current and earth leakage protection. Some LV systems require restricted earth fault protection. Consider filters to mitigate harmonics generated by the connected thyristor-based load.

Consider the type of personnel protection provided in the EVC circuit. Some countries require a residual current device (RCD) to be part of the supply circuit. Any DC leakage current over 6mAdc is not identified by a normal AC type A RCD. A type B (or F) RCD is required. These are orders of magnitude more expensive, and some designers or equipment providers may not install them. Much debate has ensured over this barrier.

Consider the requirements of galvanic isolation between the AC and DC circuits in EVC designs.

Consider DC protection to include DC insulation monitoring of the charging cable. This is the main electrical interface experienced by the public. Any DC contactors should be suitably rated as interrupting DC is physically more difficult that AC as the voltage does not pass through a zero point.

Some fuel forecourts require that the site emergency shutdown isolates all EVSEs. Consider how this may affect payment transactions, storing of the last measured values and any similar connectivity when hardwired into site ESD system.

Consider the use of fibre optic cable to connect circuits from different supplies together (e.g. a signal from the site LV supply to isolate the separately supplied EVSE).

Whilst not electrical protection as such, physical barriers like posts or bollards prevent vehicles colliding with EVSE, reducing any electrocution risk potential.

Administrative controls are viewed as lower down in the hierarchy of control table. However, these remain independent and mutually exclusive barriers. The following barriers support these control measures.

4) Isolation, intervention and reinstatement.

Consider a suitable control of work process to manage the safe interaction of personnel with electrical equipment or other such work on an EV charging site. This may include a permit to work system, lock out tag out process or safe authorisation of personnel procedure.

Consider if the type of equipment to be designed and procured will meet these systems. Suitable locking arrangements are recommended.

5) Electrical Safety rules

Consider employing suitable electrical safety rules which are clear, communicated, used and verified.

It is recommended that these rules clearly define requirements, competence and authorisation for working on or near live equipment, isolation and provide a duty of care.

6) Restricted access

Physical separation is one of the best means to prevent electrocution risks.

Consider adequate separation of the public from any live EVSE.

Consider locks or special tools to secure doors and panels. Consider separate locks for LV and HV equipment access. This assists in managing access for different authorisation levels of competent personnel.

Consider adequate signage to address live equipment dangers, no unauthorised access, or warnings of separate sources of supply.

To ensure adequate supervision at forecourts, consider charging only when the forecourt is supervised.

7) Location

EVSE should be located outside of any hydrocarbon gaseous hazardous area zones. These include the sealed forecourt apron, dispensers, tanker offloading, fill, drain and vent points or emergency exit routes.

Consider all ventilation systems to prevent possible hydrocarbon vapour entry. This includes sealing of any ducts or conduits that may interconnect a hazardous zone to a safe zone.

Storing BESS away from the public provides separation in the event of a fire.

Consider the proximity of the EVC site to other combustibles or hazards given that an EV battery may be left to burn until it self-extinguishes.

B. Mitigation barriers

Mitigation barriers are required after the risk event has occurred. Their primary purpose is to reduce the severity of the risk event to escalate to the determined consequences.

1) Secondary protection systems after an incident.

For an electrical incident to occur, the local circuit has not operated effectively, and the fault has escalated. Upstream circuitry is now required to clear the fault. Adequate protection and earthing/grounding systems are necessary to absorb the increased fault current post an incident.

Consider a high integrity earthing and grounding system of upstream circuits and protection systems.

It is recommended to grade the electrical protection system with the upstream circuit included. The integrity of this discrimination will determine the effectiveness of this barrier.

2) Ignition prevention

As both risk events can include sources of ignition, if these occur on a fuel forecourt during a fuel spillage, the risk event could escalate.

Consider means to remove ignition sources. These can include isolation of EVSE. Usually, the main emergency stop within the forecourt shop/office is linked to the relevant isolation points of the EVSE. Any battery buffered EVCs or BESS isolation will require special considerations.

Consider other flammables within the vicinity that can support escalation from the risk event.

Gas detection, as with the preventative barrier, can identify emissions leading to the escalation of heat leading to thermal runaway.

3) Emergency response.

Two types of emergency response fall within this barrier – personnel and fire related.

Consider how emergency response for an electrocution would be performed. Consider adequate signage, training, equipment, means of notification, and space around the equipment.

It is recommended that every site has a bespoke emergency response plan. This should include access and egress of people, emergency services (particularly challenging for enclosed car parks), fire mitigation measures, (sprinklers, fire doors, suppression systems) and alarm and response systems to reduce possible escalation.

Consider the extended duration of a Li-ion battery fire. In some cases, these can last for days. The heat and explosive nature of failing cells can rapidly escalate to adjacent vehicles.

Consider the consequences of excessive fire water which could be contaminated with hydrofluoric acid and other pollutants. This may affect water courses; the weight bearing loading in basements or present a flooding risk.

IX. EV CHARGING RISKS BARRIERS IN ENCLOSED AREAS

Special considerations are required when charging EV's in basements or enclosed car parks.

In the event of a fire or incident, the level of mental alertness affects one's ability and speed of evacuation from a building.

Building regulations consider residential accommodation (in particular hotels) and shops/commercial properties. higher risk category than commercial premises due to high occupancy densities, more potential for disorientating layouts, unfamiliar occupants and increased potential for rapid fire development. Commercial properties historically have a lower life risk, with buildings often involving large volumes and effective smoke control with occupants generally more alert. [14]

Assembly/recreational, may sit between these two. Life risk in offices is understood to be low where occupants are generally familiar with the premises and fire loads are consistent and appropriately managed.

A. Risks

A different probability of disorderly evacuation applies when calculating the risk for different building types.

The CPO has no control over the EV or EV battery condition. The CPO does have control over any owned BESS.

A car fire in a parking bay is already a known risk. An ICE fire has the same heat release rate as an EV (although EV battery may burn longer and create more focused heat, similar to a jet or plastic fire)

Charging an EV presents a slightly higher risk of EV battery failure than simply parking. However the frequency of fire in a BESS as part of, or in support of EVSE is not well understood and with a much larger energy capacity, could potentially result in hazards with greater consequences.

In most cases, CPO reputational impact is perceived to be the key risk differential from introducing chargers. There could be legal repercussions if failure of the EVSE leads to injury or fatality.

B. Bow tie

Further to the general bow tie shown above for EV charging sites, a specific risk bow tie helps frame the enclosed parking barriers.

Figure 7 (see Appendix B for a larger format) shows the specific bow tie applicable to enclosed areas.

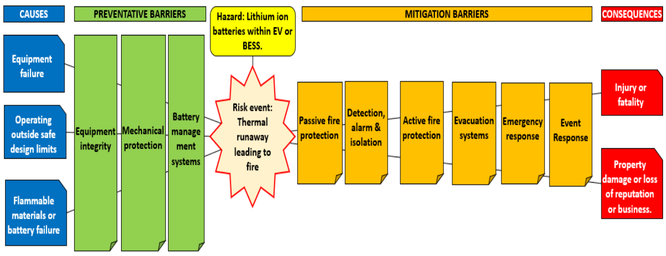

Figure 7 Enclosed area EV charging bow tie

The following apply:

1) *Hazard:*

Lithium-ion batteries within EV or BESS

2) *Risk:*

Fire. While electrocution is still a risk, in this case the focus is solely on fire.

3) *Causes:*

a) *Failure of equipment*

Include the battery, EVC, or any EVSE.

b) *Operating outside equipment's safe operating limits.*

Include battery failure initiators discussed above (electrical, mechanical or chemical abuse)

c) *Flammable materials.*

Consider the risk of other vehicles or any other combustible material that may propagate a fire.

4) *Preventative Barriers*

a) *Equipment integrity – charging and charged.*

EVCs without BESS are relatively low risk failure items as they consist mainly of electrical components. A range of detection features should be considered including temperature, electrical overload, over current and earth fault protection, DC insulation and internal faults.

EVCs incorporating BESS can be supplied with preventative systems such as BMS achieving a known level of functional safety integrity e.g. SIL2, and mitigation systems such as smoke detection, gas and temperature monitoring. The CPO has a duty to understand these risks and specify the correct type and number of barriers to control these risks. The CPO has better control over the risks of BESS.

b) *Mechanical protection*

Physical protection to prevent mechanical damage from an impact to equipment can include bollards, kerbs or wheel stops.

Consider encasing batteries in a robust construction. EVs usually design crash-proof casings to house the battery systems.

c) *Battery management system (within vehicle)*

Over charging, charging at too high a rate or charging failing/failed batteries can lead to battery integrity concerns. The BMS should be configured to detect these occurrences. As the BMS is part of the vehicle, as CPO, this is a challenging barrier to manage.

5) *Mitigation barriers*

Due to the uniqueness of each installation, local regulations etc. for every site should develop a specific emergency response plan that includes the barriers below.

a) *Passive fire protection*

A key mitigation barrier includes the thermal rating of the surrounding concrete construction. (e.g., a fire rating of 4 hours is recommended by the London Fire Brigade [10]). A suitable concrete basement ceiling can offer significant fire-withstand properties to the building above.

Consider smoke management – natural or forced ventilation – and how the latter is energised. Note the reflected heat off the ceiling and walls in an enclosed area is significantly more than in an open area.

b) *Detection, alarms and isolation*

Consider how fires may be detected within a battery (see Preventative barrier – Equipment integrity) and within a building.

Smoke alarms may be required within EVC's or other electrical equipment.

Consider how these alarms communicate to a place where an effective response can be made.

Consider how fire alarms are communicated to the wider affected or at-risk population.

c) *Active fire protection*

Consider sprinkle or suppression systems. Although unlikely to quench an EV or Li-ion battery fire, these may mitigate escalation.

Consider internal fire water mains in terms of sizing, back up, integrity and the ability to operate in the event of a battery fire.

d) *Evacuation systems*

All fire evacuation plans should be well signposted. These should be visible even when there is a power outage.

e) *Emergency response procedures*

Consider firefighting access, length of hoses from most suitable hydrant, routes and any alternative routes.

Alert the local fire brigade of the additional risk of EV charging and update any fire risk procedures.

f) *Event response*

Consider the effects of copious quantities of water on the building design – weight of water, flooding of lower floors, and contaminated water management.

Consider the effects of smoke damage to the building and or its neighbours and occupants.

6) *Consequences*

As per above, the same main consequences result when considering enclosed car parking areas.

a) *Injury, Electrocution or fatality*

As this scenario does not deal with electrical energy, the personnel-related consequence focusses on injury or fatality from a fire or as a result of a fire within an enclosed car park.

b) *Property or reputational damage and/or loss of business.*

As per the example above, any safety incident, or fire could result in damage to the operator's reputation or even in a closure of the site, or, if significant, the business itself. Escalation risks affecting any building above or adjacent to the enclosed car park can be significant.

Regardless of the legal responsibility, the CPO may face an unintended reputational risk.

These consequences should drive CPO's to seriously consider the risks of enclosed areas for EV charging or BESS storage locations.

X. GENERAL EV CHARGING RISK MITIGATIONS

A. Standards

ISO 15118 – "Road Vehicles – Vehicle to grid communication interface" provides a well-designed and documented, future-proof standard addressing vehicle to EVC communications. Globally applicable, covering AC, DC, wireless and vehicle to grid (V2G) charging within a constrained utility grid capacity, this standard makes it possible to match the grid's capacity to the energy demands of a growing number of EVs

B. Application of process safety to EVSE.

Applying functional safety. Hazard identification (HAZID), Hazard and Operability (HAZOP) studies and risk assessment are some of the tools industries are applying to identify risks. These tools now include equipment manufacturers and thus the whole industry benefits.

C. Off gas emission detection

Recent developments in incipient cell failure identification equipment connected to a suitable shutdown system can greatly reduce the escalation risks of battery failures. Traditional gas detection methods have been less effective. This is seen as a significant fire management strategy that currently meets many insurance company requirements.

XI. CONCLUSION

This paper discusses the use of a bow tie model for risk assessment and applies this to EV charging sites with special focus on high-risk sites, namely fuel forecourts and enclosed locations. Preventive and mitigation barriers are discussed with key points for the reader to consider.

While many barriers are common to industry today and can be implemented effectively, the issue of lithium-ion battery integrity remains a challenge for industry. EV batteries are encased deep within the vehicle and not within the CPO's control. Detecting battery failure is difficult. Li -ion batteries fail catastrophically and currently there few effective fire management methods of early extinguishment known to CPOs.

As the number of EVs in use increase, charging locations become increasingly difficult to site. BESS is promoted where electrical infrastructure cannot support fast charging EVSE. These risks may escalate with the concomitant negative consequences.

Industry would do well to heed the advice offered and remain abreast of other risk management mitigations within this growing industry.

NOMENCLATURE

BESS	Battery energy storage systems
CPO	Charge point operator
EPR	Earth potential rise
EV	Electric vehicle
EVC	Electric vehicle charger
EVSE	Electric vehicle supply equipment
GPR	Ground potential rise
HMI	Human machine interface
ICE	Internal combustion engine vehicle
RCD	Residual current device

II. ACKNOWLEDGEMENTS

The author would like to thank Nick Davies, Gholam-Hasan Molayem, Alex Waslin and the PCIC Technical committee for their review.

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XIII. VITA

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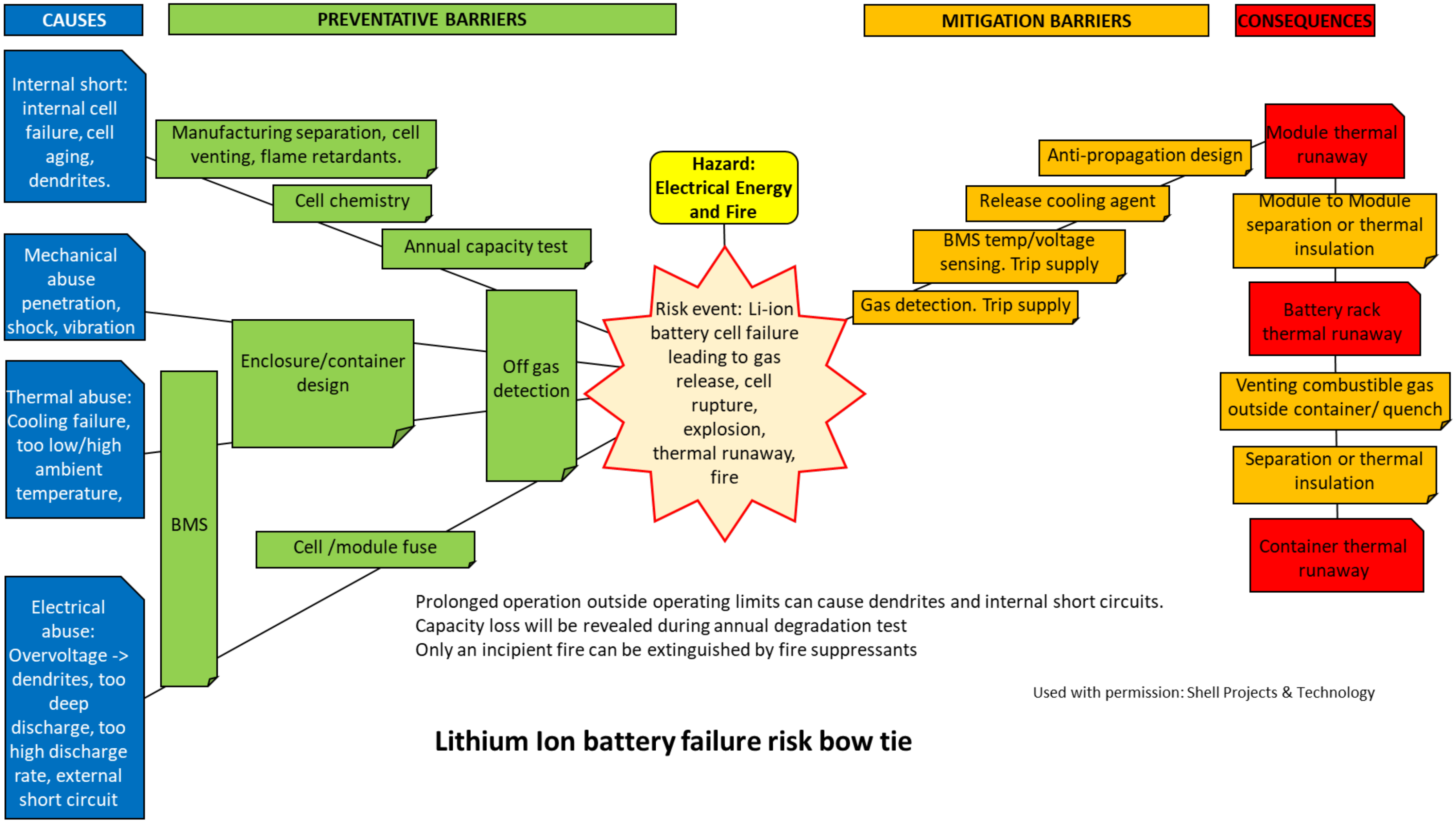
XIV. APPENDIX

A. APPENDIX A



Used with permission: Shell Projects & Technology

Lithium Ion battery failure risk bow tie

B. APPENDIX B

FIGURES IN DETAIL

The following figures are shown in a larger format for clarity.

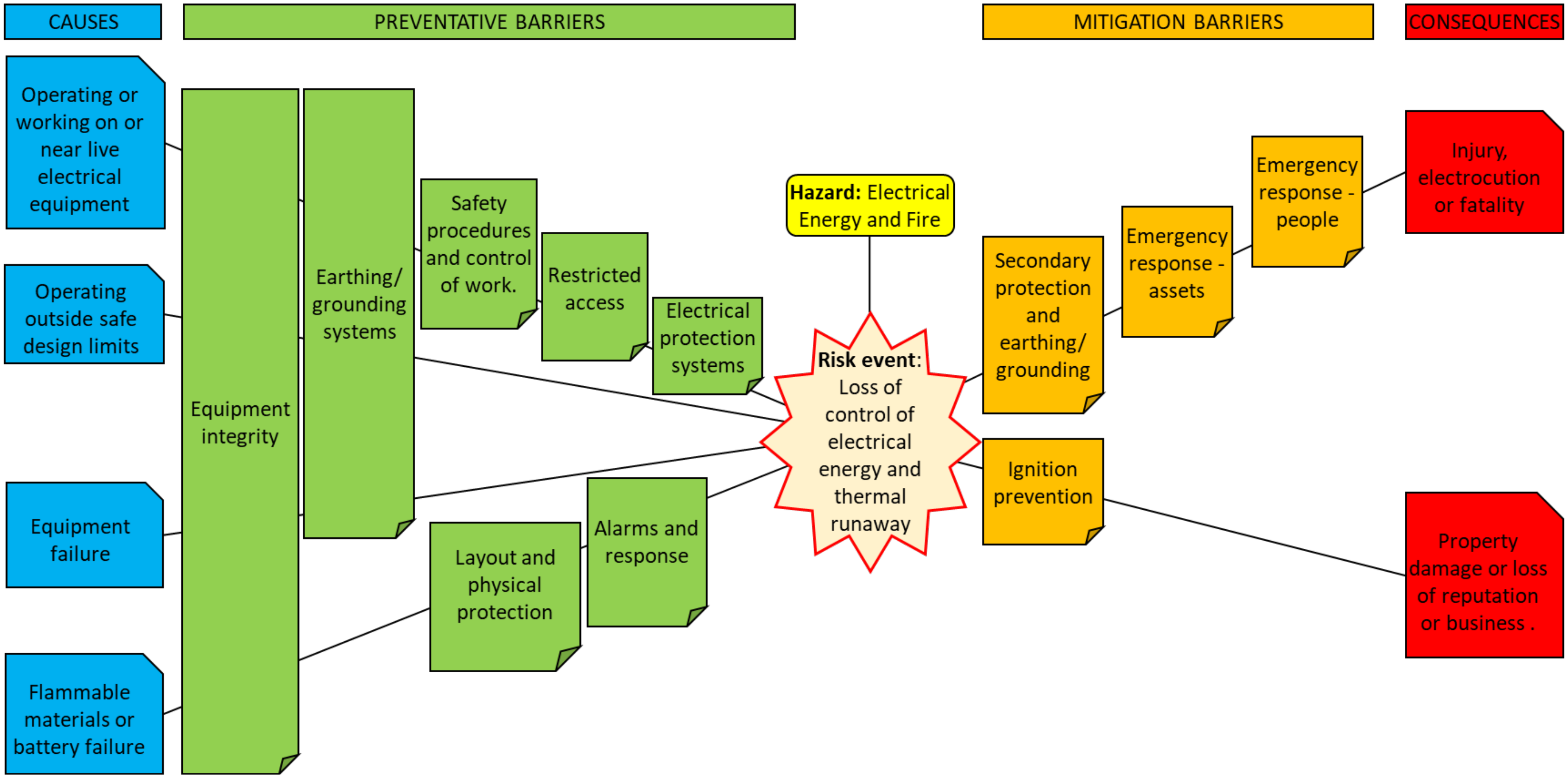


Figure 6. Barriers added to the bow tie model

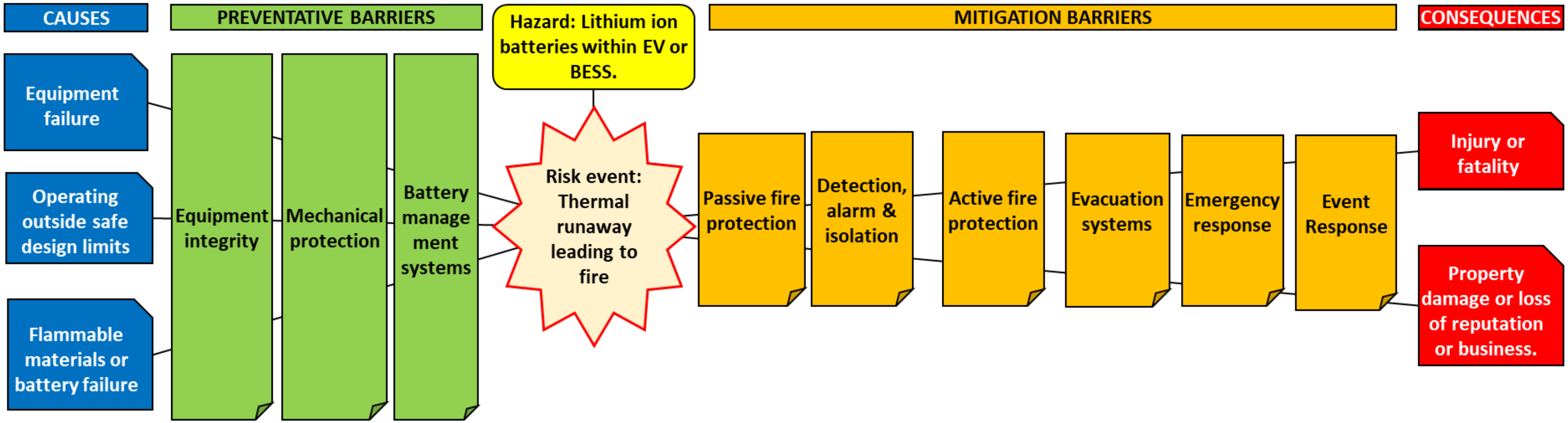


Figure 7 Enclosed area EV charging bow tie