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Electrification in Deep Underground Mining: A Systems Analysis of Battery Electric Vehicle Failure Pathways and Operational Risk Dynamics

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Abstract

Battery Electric Vehicles (BEVs) are increasingly deployed in deep underground hard-rock mining to reduce diesel emissions, ventilation demand, and heat load. However, large-format NMC lithium-ion systems introduce distinct failure modes shaped by the confined geometries, mechanical loading, and ventilation constraints of subsurface environments. This study integrates electrochemical evidence, large-scale fire-testing data, OEM design documentation, and operational observations from an anonymised deep mine to characterise the dominant risk pathways associated with BEV operation. Results show that electrical instability, mechanical degradation, thermal escalation, early toxic-gas venting, and pack-level propagation interact nonlinearly, amplifying the likelihood and consequences of failure relative to surface conditions. Ventilation patterns influence gas accumulation and dispersal, while ground-induced vibration and microseismicity elevate the probability of latent cell damage. Limitations in battery-management-system diagnostics under dynamic duty cycles further constrain early detection. The analysis demonstrates that BEV safety in deep mines is a system-level challenge that requires integrating equipment design, thermal management, ventilation engineering, maintenance practices, human factors, and emergency-response planning. The findings support a technically grounded framework for electrification and identify research priorities related to underground thermal-runaway behaviour, advanced diagnostics, multi-species gas modelling, and next-generation battery architectures.

Keywords: *Battery Electric Vehicles (BEVs), Lithium-Ion Battery Safety, Thermal Runaway, Toxic Gas Evolution, Underground Mining*

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1. Introduction (H2 Densified Version)

Electrification has become a central strategy in the transformation of underground hard-rock mining as operators confront rising ventilation costs, decarbonization pressures, and increased scrutiny of worker exposure to diesel particulates and heat. Battery electric vehicles (BEVs) offer measurable reductions in on-site emissions and thermal loads, and support improved operational efficiency in deep mines where ventilation demand is a significant cost driver[1,2]. Their benefits, however, coincide with a technically complex risk environment arising from the physical behaviour of large-format NMC lithium-ion systems under the mechanical, thermal, and atmospheric constraints of underground mines.

NMC lithium-ion batteries exhibit well-established pathways to runaway under abuse conditions, including SEI layer degradation, lithium plating, electrolyte volatilisation, and oxygen release from cathode structures[3-5]. Once initiated, these reactions develop rapidly and are strongly influenced by module-level architecture, thermal boundary conditions, and cooling performance. Underground mines amplify these behaviours. Confined geometries limit heat rejection; ventilation circuits do not always provide consistent airflow; and localised geological heat contributes to narrow thermal margins. Under these conditions, even moderate deviations in cell temperature or pressure can accelerate internal decomposition reactions.

Mechanical conditions further complicate the operational envelope of BEVs. Deep mines experience vibration from tramming, impact loading on uneven footwalls, and periodic microseismicity related to stress redistribution. Laboratory studies demonstrate that relatively small mechanical deformations can initiate latent defects or internal shorts that evolve into runaway under subsequent electrical or thermal stress[6,7]. Handling during battery swapping introduces additional exposure, particularly at high-voltage connectors, where misalignment or wear may increase resistance and cause localised heating.

Gas evolution is a critical dimension of BEV risk. Empirical studies show that early venting from NMC cells releases hydrogen fluoride, carbon monoxide, hydrocarbons, and other toxic or flammable species at concentrations that can impair human performance long before visible flames develop[8-10]. In underground settings, airflow constraints promote stratification and backlayering, enabling contaminants to migrate into adjacent headings or obstruct egress routes. The spatial and temporal characteristics of this early-stage venting challenge traditional underground fire-response models, which are typically calibrated to diesel or conveyor fires rather than electrochemical-origin events.

The complexity of BEV duty cycles adds diagnostic uncertainty. BEVs routinely transition between high-discharge tramming, regenerative braking, and variable loading during mucking. These states introduce conditions not always captured in BMS models calibrated under laboratory regimes. Sensor drift, simplified state-estimation algorithms, and thermal gradients across modules may reduce diagnostic accuracy[11,12]. As a result, early detection of thermal or electrical anomalies cannot rely solely on BMS-generated warnings.

Mine-level consequences of BEV failure are significant. Equipment immobilisation on single-entry ramps can obstruct evacuation, impede emergency access, and compromise ventilation control. Gas accumulation or flame impingement can damage infrastructure, including electrical installations and ground-support elements. Conventional emergency-management practices do not fully account for the staged progression of lithium-ion failures or the temporal separation between venting, ignition, and propagation[13,14].

This study synthesises electrochemical evidence, large-scale fire-testing results, OEM documentation, and operational insights from a deep hard-rock mine to establish a technically grounded framework describing the dominant risk pathways associated with BEV deployment. In doing so, it clarifies the interactions among electrical, mechanical, thermal, and atmospheric processes most relevant to deep mines. It provides a basis for evaluating mitigation strategies across equipment, operational, and system levels.

2. Background and Theoretical Context

The deployment of high-capacity NMC lithium-ion battery systems in underground mines introduces risks shaped by the interplay of electrochemical behaviour, thermal boundary conditions, mechanical stresses, and the confined geometry of subsurface environments. A coherent theoretical framework must therefore integrate insights from battery science, fire dynamics, systems engineering, and mining operations to characterise how failures originate, evolve, and interact with mine infrastructure and ventilation.

NMC batteries dominate heavy-duty BEV platforms due to their favourable energy density, thermal efficiency, and established manufacturing base. Their stability depends on the controlled intercalation of lithium ions between a graphite anode and a layered metal-oxide cathode within a flammable organic electrolyte. Deviations from nominal operating conditions initiate a sequence of degradation processes. Elevated temperatures accelerate SEI breakdown, electrolyte vaporisation, and cathode oxygen release, each of which increases internal pressure and heat generation[3-5]. At critical temperatures,

typically above 150°C depending on formulation, these reactions become self-accelerating, leading to thermal runaway. Module density, cell spacing, and thermal-management design strongly influence the rate and extent of this escalation.

Modelling advances have clarified the reaction kinetics and heat-transfer behaviour underlying runaway. Thermal-runaway models show that even modest reductions in heat-dissipation capacity significantly lower the threshold at which decomposition becomes self-sustaining[15]. Industrial battery packs, with hundreds of tightly coupled cells, inherently possess high thermal inertia, meaning that localised defects cannot dissipate heat effectively. Recent full-scale NMC sub-pack tests confirm that heat accumulation, rather than instantaneous ignition, often governs propagation[16]. The time lag between early venting, self-heating, and eventual flame onset complicates detection and response, particularly in underground settings where sensor coverage and operator visibility are limited.

Mechanical loading is a critical factor in initiating latent battery defects. Underground mines impose persistent vibration from tramming, dynamic loading during mucking, and episodic microseismicity associated with stress redistribution. Experimental studies demonstrate that even minor deformation—compression, bending, or puncture—can introduce microstructural defects that develop into internal short circuits under thermal or electrical load[6,7]. Battery swapping, a common practice in high-productivity mines, adds handling-related exposure: misalignment during insertion or extraction can degrade connector interfaces, elevate contact resistance, and increase localised heating during operation. These mechanical factors must be integrated into any realistic assessment of BEV risk in underground environments.

Fire dynamics add further complexity. Early venting in NMC failures produces HF, CO, hydrocarbons, and other toxic or flammable species at concentrations that exceed occupational exposure limits even before flaming occurs[8,9]. The dispersion of these gases depends on ventilation conditions, drift geometry, and buoyancy effects. The restricted volumes and airflow discontinuities characteristic of underground mines promote stratification, stagnation zones, and backlayering, enabling contaminants to migrate into working areas or obstruct egress routes. These behaviours differ markedly from conventional diesel or conveyor fires and require distinct analytical treatment[10]. Even in non-flaming events, gas composition alone may render areas untenable.

Pack architecture further shapes propagation behaviour. BEV battery packs incorporate physical separators, thermal barriers, and liquid-cooling channels to limit heat transfer and retard propagation. However, the performance of these barriers is highly sensitive to temperature gradients, coolant-flow integrity, and the alignment of thermal interfaces. Compromised cooling—whether due to pump failure, coolant leakage, or blockages—reduces the capacity of the pack to accommodate thermal perturbations. Empirical research shows that propagation can still occur through conduction and internal venting despite nominal barrier architecture, particularly when cells share structural pathways for heat transfer[7,17].

Risk-analysis theory provides the integrative framework needed to evaluate such interacting hazards. Traditional mining risk assessments often rely on deterministic approaches that treat ignition sources, fuel loads, and ventilation outcomes as discrete components. Lithium-ion risks, however, require probabilistic reasoning due to the nonlinear interaction among mechanical, electrical, and thermal conditions. Bow-tie analysis, fault-tree logic, and event-sequence modelling offer suitable structures for describing how initiating events escalate into full-scale incidents and how preventive and mitigative controls influence transition probabilities[18]. For BEVs, initiating events include internal shorts, coolant-system failure, electrical abuse, or mechanical damage. The consequences span toxic-gas release, thermal propagation, equipment immobilisation, and mine-level ventilation impairment. The interconnected nature of these pathways underscores the necessity of system-level frameworks.

Human and organisational factors must also be considered. BEV operation introduces high-voltage systems, evolving diagnostic regimes, and failure signatures that are unfamiliar to personnel accustomed to diesel machinery. Operator recognition of early thermal-distress cues, adherence to charging protocols, and precision in battery-swapping practices are essential preventive barriers. Research in resilience engineering emphasises that technological safety performance depends heavily on the organisation's capacity to detect weak signals, manage uncertainty, and adapt procedures[19]. The transition to BEVs, therefore, requires changes not only in equipment but also in training, supervision, and safety culture.

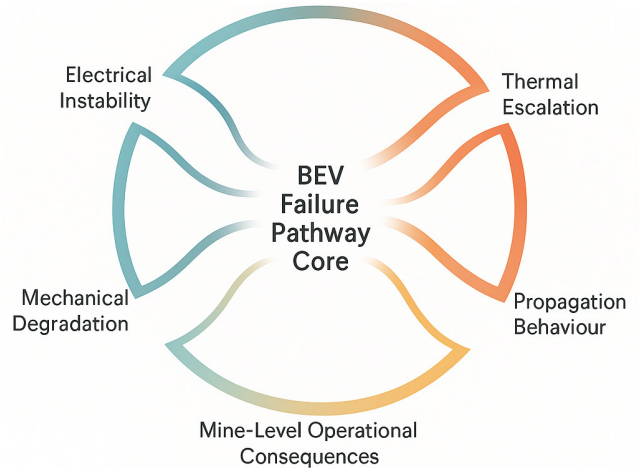


Figure 1. Integrated systems framework illustrating the interacting hazard domains governing Battery Electric Vehicle (BEV) failure pathways in deep underground mining, including electrical instability, mechanical degradation, thermal escalation, early toxic-gas evolution, propagation behaviour, and mine-level operational consequences.

Lastly, electrification must be situated within the broader context of sustainability and life-cycle risk. While BEVs reduce operational emissions, they introduce upstream and downstream risks associated with manufacturing energy intensity, resource extraction, and end-of-life recycling[20,21]. As chemistries and pack architectures evolve, so too will their hazard profiles. Mines implementing electrification must be prepared for continuous updating of risk models as technical and scientific knowledge advances.

Together, these theoretical components establish the foundation for analysing BEV behaviour in underground settings. They clarify how electrical, mechanical, thermal, environmental, and organisational factors interact to shape risk and why BEV integration requires a fundamentally different analytical approach than that used for conventional mobile-equipment hazards in figure 1.

3. Materials and Methods

This study employs a multi-layered analytical framework integrating electrochemical evidence, large-scale fire-testing data, OEM technical specifications, and operational characteristics of an anonymised deep hard-rock mine. The objective is to characterise the dominant risk pathways associated with BEV deployment under real underground conditions. The methodology emphasises system-level coherence, acknowledging that electrical, mechanical, thermal, and environmental factors in underground mines interact in ways that cannot be represented through single-variable or laboratory-only analysis.

The anonymised mine is representative of modern deep, high-stress operations, with extensive ramp systems, variable footwall conditions, episodic microseismicity, and areas where ventilation flow is discontinuous or constrained. The BEV fleet includes a battery-electric haul truck and an LHD unit, each equipped with modular NMC lithium-ion battery packs, liquid cooling, and high-voltage power electronics. These units operate across diverse headings where thermal gradients, ground conditions, load cycles, and congestion vary substantially. Observed duty cycles include high-load tramming, repeated acceleration and deceleration, and regenerative braking on long declines—conditions known to produce rapid transitions in current draw, internal resistance, and heat generation.

The primary analytical structure is a modified bow-tie framework constructed to capture the multidimensional failure environment of industrial BEVs. Thermal runaway functions as the top event, with initiating events mapped across electrical, mechanical, thermal, and operational domains. Initiating events include internal short circuits, electrical abuse conditions, thermal-management system degradation, mechanical deformation of cells or modules, software or sensor anomalies in the BMS, and external heat flux from equipment or geological sources. These initiating events reflect mechanisms documented in electrochemical and fire-science literature[3,4,6,7]. Preventive controls include BMS logic, thermal-management architecture, pack-housing design, charger interlocks, and maintenance practices. Mitigative controls include pack-level fire-resistance measures, mine-ventilation response, operational isolation protocols, and emergency-egress strategies.

The bow-tie model is supported by three evidence streams. First, empirical data from large-scale NMC thermal-runaway testing inform assumptions about gas-evolution timing, venting temperatures, flame characteristics, propagation intervals, and the role of module spacing and barrier performance[10,16]. Second, OEM documentation—including battery schematics, cooling-system layouts, connector architecture, and safety-logic descriptions—provides insight into

engineered barrier performance and potential points of vulnerability. Third, operational observations from the mine contribute contextual parameters, including typical load cycles, geotechnical exposure, ventilation variability, and the geometry and accessibility of charging and swapping areas.

A qualitative systems-engineering assessment complements the bow-tie model by examining how geotechnical, thermal, and ventilation conditions shape the operational stability of BEVs. Geotechnical assessments consider vibration exposure, ground-support conditions, and microseismicity, all of which can impart mechanical stresses capable of degrading cells, cooling conduits, or high-voltage terminals. Thermal assessments consider ambient-temperature variability, heat accumulation in constrained headings, and interaction effects between BEV thermal output and mine-ventilation capacity. Fire-dynamics considerations include gas buoyancy, stratification, ignition potential, and the influence of drift geometry on heat transfer and contaminant dispersion.

Human-factors analysis is incorporated due to its importance in initiating or preventing failure sequences. Tasks such as battery swapping, connector engagement, troubleshooting, and abnormal-event recognition introduce opportunities for procedural variance. Research highlights that diagnostic gaps, incomplete mental models, and inconsistent procedural adherence contribute to risk in technologically complex environments[19]. Training materials, operating procedures, and situational-awareness expectations within the mine are therefore examined as integral components of the risk system.

Triangulation is used to synthesise evidence. Electrochemical and fire-testing insights are mapped against OEM design constraints to evaluate whether observed failure behaviours align with equipment-level safety assumptions. These are then interpreted considering environmental and human factors unique to the underground context. This integrated analysis enables identification of the most credible failure pathways, the conditions under which they become probable, and the potential severity of mine-level consequences.

While the study does not employ quantitative probabilistic modelling—owing to limited industrywide incident data and the evolving nature of BEV technology—the qualitative synthesis provides a robust platform for identifying hazard concentrations, system interdependencies, and operational touchpoints where preventive and mitigative controls are most needed. The methodology, therefore, supports a technically grounded interpretation of BEV risk dynamics and provides a foundation for the results and discussion that follow.

4. Results

The integrated analysis identifies a set of interdependent hazard domains that collectively define the risk landscape for BEV operation in deep-underground mines. These domains—electrical instability, mechanical degradation, thermal escalation, toxic-gas evolution, propagation dynamics, and mine-level operational consequences—interact in ways that amplify the likelihood and severity of failure relative to surface or laboratory conditions. The results highlight how these interactions emerge from the physical constraints of the mine environment and the operational realities of industrial BEV duty cycles.

Electrical instability represents a primary failure vector. Duty-cycle observations show that BEVs at the study site experience rapid transitions among high-load tractive effort, regenerative braking, and variable power demand, producing fluctuating current profiles and thermal gradients that increase internal stress on the anode, cathode, and SEI layer. These transitions increase the risk of lithium plating and degradative reactions, which reduce charging stability and boundary-condition tolerance[3,5]. Even minor electrical anomalies may propagate because module density and thermal coupling reduce the ability of localised defects to dissipate heat effectively[4]. BMS performance is limited by sensor placement, thermal gradients, and algorithmic simplifications that may under-estimate or mischaracterise early-stage anomalies, particularly in dynamic duty cycles[11,12]. As a result, electrical failure pathways are more uncertain in underground BEVs than in surface applications in table 1.

Mechanical degradation forms the second dominant hazard domain. Deep hard-rock mines generate vibration, impact loading, and periodic microseismicity, all of which impart mechanical stresses to battery packs, cooling conduits, cell casings, and high-voltage connectors. Experimental evidence demonstrates that relatively small deformations—compressive, flexural, or penetrative—can induce microstructural changes that evolve into internal short circuits under subsequent thermal or electrical

Table 1. Hazard domains, initiating events, and escalation mechanisms for underground BEV operation

Hazard Domain	Initiating Events	Escalation Mechanisms
Electrical Instability	Internal shorts; overcurrent Sensor drift; SOC Misestimation	Localized heating Accelerated SEI breaakdown Thermal imbalance
Mechanical Degradation	Vibration; impact loading Microseismicity Connector wear	Structural deformation Resistance increase Insulation breach
Thermal Constraints	Inadequate cooling Heat accumulation High ambient temiperature	Reduced thermal margins Runaway onset
Gas Evolution	Early venting Electrolyte vamorization	HF/CO accumulation Reduced visibility
Propagation	Barrier overload Vent ignition	Module-to-module heat transfer Structural compromise

load[6,7]. Operational observations show that repeated battery-swapping cycles introduce alignment variability and cumulative connector wear, elevating resistance and creating potential hot spots during discharge. These findings indicate that mechanical robustness is not purely a design attribute but a function of ongoing operational exposure.

Thermal behaviour constitutes the third hazard domain: ambient-temperature variability, poor airflow uniformity, and localised geological heat inflow, with narrow safety margins for NMC systems. BEVs operating in constrained headings may encounter heat accumulation that elevates pack temperature despite nominal cooling performance. Thermal-runaway thresholds depend on cell chemistry, state of charge, and cooling effectiveness, but once internal decomposition reactions begin, heat generation typically outpaces dissipation under confined underground conditions[22]. Large-scale tests show that pre-runaway venting may persist for tens of minutes before ignition, producing a dangerous interval in which failure is underway but not externally obvious[16]. This creates operational ambiguity: The system is degrading, but classical visual or audible cues may be absent, and available intervention windows are narrow.

Toxic-gas evolution presents a fourth critical hazard domain. Early venting generates hydrogen fluoride, carbon monoxide, and hydrocarbons at concentrations exceeding occupational exposure limits before flame onset[8,9]. Underground dispersion behaviour differs from that in open air in (Figure 2). Constrained drifts promote stratification and stagnation, allowing gases to accumulate or migrate into adjacent headings, even when initial venting is small. Ventilation mapping at the anonymised mine shows several zones with low or recirculating flow conditions, meaning gas concentrations can rise quickly after venting begins. The temporal separation between venting and ignition complicates both operator recognition and emergency response. These findings confirm that gas toxicity—not flame spread—is often the earliest and most consequential threat in BEV failures underground.

Propagation dynamics form the fifth hazard domain. Although BEV packs incorporate thermal barriers, cell spacing, and liquid cooling intended to retard propagation, empirical testing demonstrates that these measures are partially effective and sensitive to real-world conditions (Figure 3). Propagation has been observed between modules when barriers reach thermal tolerance limits or when vented gases ignite within the pack architecture, producing pressure pulses that compromise adjacent casings[7,17]. The anonymised mine's BEVs employ liquid cooling, but any degradation in coolant flow or interface integrity may accelerate heat accumulation. The confined geometry of underground headings increases the radiative and convective heat feedback to the external pack housing, reducing the likelihood of self-limiting failure as in the Figure 4.

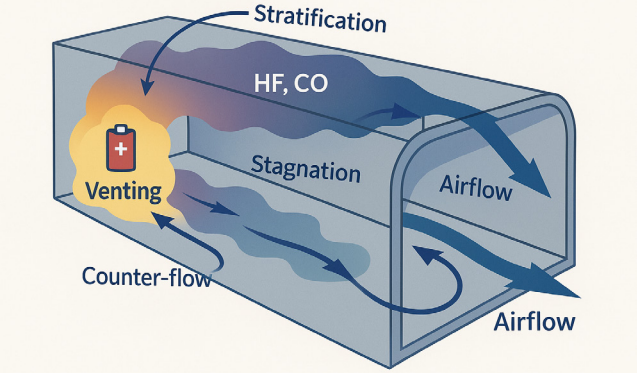


Figure 2. Conceptual model of gas-dispersion behaviour in underground headings, illustrating stratification, stagnation, and counter-flow transport of HF- and CO-rich plumes following early venting from a failing BEV.

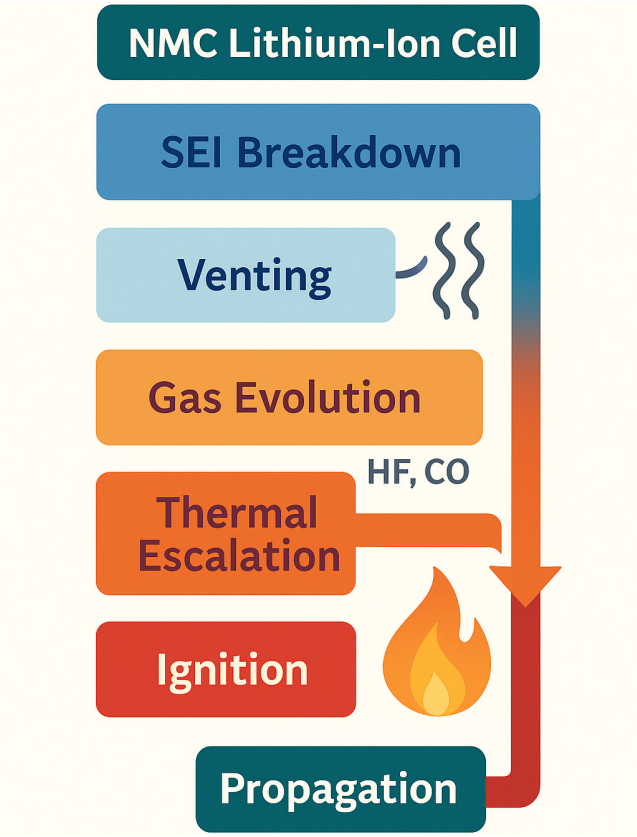


Figure 3. Schematic representation of the staged progression of thermal runaway in NMC lithium-ion cells, highlighting early venting, gas evolution, internal temperature rise, ignition, and potential propagation under confined underground thermal boundary conditions.

The sixth domain concerns mine-level operational consequences. BEV immobilisation in a critical airway—such as a long single-entry ramp—can obstruct evacuation

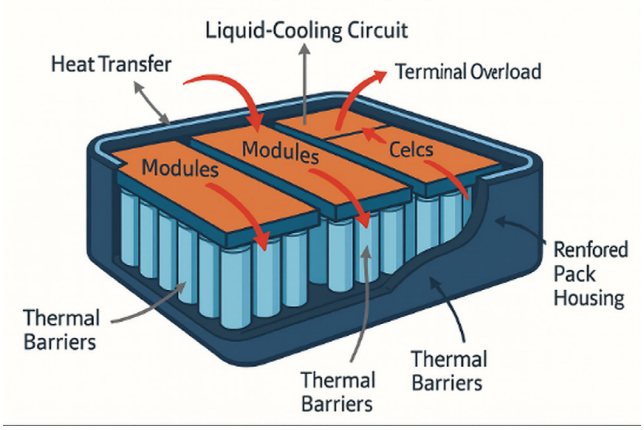


Figure 4. Structural features of a typical industrial NMC battery pack, including modules, thermal barriers, and liquid-cooling circuits, with arrows illustrating potential propagation pathways during thermal runaway escalation.

and emergency access. Gas accumulation may render travelways untenable, while heat release can damage infrastructure, including power cables, ventilation controls, and ground-support elements (Figure 5). The mine's ventilation network, designed primarily for diesel dilution and heat management, does not inherently account for HF-rich plumes or multi-species gas evolution. CFD-style inference suggests that in specific headings, gas layers may migrate counter to bulk airflow, creating exposure hazards in areas not directly adjacent to the failure. Furthermore, the requirement to isolate the affected zone may disrupt airflow balance elsewhere, reducing available intake volumes in production areas and affecting personnel safety at distances far from the initiating event.

Across all hazard domains, the analysis shows that BEV failure pathways are nonlinear and mutually reinforcing. For example, mechanical degradation may increase electrical instability; electrical anomalies may elevate thermal loads; thermal escalation may accelerate gas generation; gas accumulation may create ignition potential; and equipment immobilisation may convert a contained failure into a mine-level emergency. These results underscore that BEV risks cannot be mitigated through single-barrier interventions but require coordinated system-level strategies addressing equipment design, maintenance, operator competence, mine planning, and ventilation engineering simultaneously.

The combined findings reveal a coherent pattern: underground mining amplifies the intrinsic hazards of lithium-ion systems through constrained geometry,

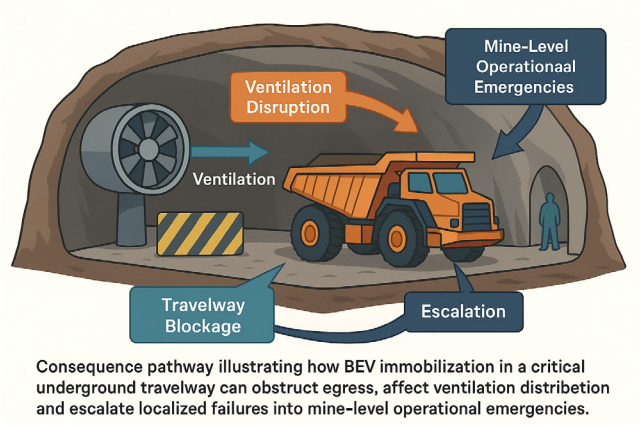


Figure 5. Consequence pathway illustrating how BEV immobilisation in a critical underground travelway can obstruct egress, affect ventilation distribution, and escalate localised failures into mine-level operational emergencies.

limited heat dissipation, complex airflow, mechanical variability, and the criticality of travelway accessibility. BEV risk in deep mines is therefore a function of both electrochemical processes and environmental context. Understanding these interactions is essential for developing credible mitigation strategies and for informing the operational, engineering, and regulatory decisions that govern electrification.

5. Discussion

The results demonstrate that BEV deployment in deep underground mines produces a risk environment shaped by the interaction of electrochemical instability, mechanical loading, thermal constraints, gas-evolution behaviour, and mine-level operational dependencies. These interactions highlight the inadequacy of treating battery-related hazards as isolated technical failures. Instead, BEV risk manifests as a coupled-systems phenomenon in which environmental, operational, and technological conditions converge to amplify the likelihood and consequences of failure.

A principal implication is the dominant influence of underground environmental constraints on failure progression. Laboratory studies offer important insight into initiation and propagation mechanisms, yet the confined geometries and limited ventilation capacities of underground mines materially alter these behaviours. Early venting of HF, CO, and hydrocarbons occurs before visible flame development and at concentrations

Table 2. Interaction of underground environmental factors with BEV failure pathways

Interaction of Underground Environmental Factors with BEV Failure Pathway		
Environmental Factor	BEV Failure Pathway	
	Thermal Runaway	BEV Immobilisation
Temperature	Elevated temperatures accelerate TR risk	Extreme cold hinders battery performance
Humidity	Moisture ingress can degrade cells	Humidity impacts electrical components
Airflow	Ventilation disperses HF and CO	Air movement dilutes and disperses HF and CO
Mine Fires	Fire spread raises external thermal load	Smoke reduces visibility and access
Mine Geometry	Confinement enhances thermal accumulation	Bottlenecks increase blockages and delays

that can quickly exceed occupational thresholds[8-10]. In the underground context, these gases do not disperse predictably. Instead, stratification and recirculation may delay or obscure detection and expose personnel well before ignition. These challenges are assumptions embedded in traditional mining emergency frameworks that prioritise flame impingement or smoke visibility as primary hazard indicators in Table 2.

Mechanical and geotechnical considerations are equally central. The anonymised mine, like many deep operations, experiences vibration, uneven ground conditions, and episodic microseismicity. These forces impose mechanical stresses that can degrade pack housings, cooling lines, and cell interfaces. Empirical research confirms that seemingly minor deformation can generate microstructural changes that evolve into internal short circuits or promote thermal escalation[6,7]. As BEVs frequently traverse areas with variable ground support and loading environments, mechanical exposure becomes a persistent risk driver independent of electrical behaviour.

Limitations in BMS diagnostic capability further compound risk. Lithium-ion systems require accurate estimation of state-of-charge, temperature, and internal resistance, yet dynamic underground duty cycles introduce conditions that exceed model assumptions. Regenerative braking, steep-gradient tramming, and variable loading generate non-linear electrochemical responses that may reduce BMS predictive accuracy[11,12]. Consequently, early warning signals may be absent, delayed, or ambiguous. This suggests that BEV safety cannot rely solely on on-board diagnostics but must be supported by external detection strategies, environmental

monitoring, procedural discipline, and conservative operational decision-making.

Propagation potential remains a critical concern. Even with thermal barriers, spacing, and cooling, pack-level propagation has been observed under test conditions[7,17]. In underground mines, the thermal boundary conditions surrounding the equipment differ markedly from surface environments. Confined headings increase radiative and convective heat feedback, reducing the likelihood that a runaway event remains self-contained. Once initiated, propagation may compromise equipment structure, disable onboard controls, and create immobilisation hazards in critical travelways.

The operational consequences of BEV immobilisation are particularly significant. Many underground mines depend on long, linear ramp systems for both intake ventilation and emergency egress. BEV failure on such routes poses a systemic hazard: obstructed travelways can isolate personnel, impede rescue operations, disrupt ventilation flows, and allow toxic gases to migrate into remote areas of the mine. The temporal characteristics of lithium-ion failure—particularly the interval between early venting and complete runaway—introduce further complexity. During this period, the equipment may remain mobile or appear stable, creating ambiguity for operators and supervisors responsible for evacuation or isolation decisions in figure 6.

Organisational and human factors shape how these technical risks manifest in practice. Electrification introduces operational demands distinct from those of diesel equipment, including sensitivity to connector condition, adherence to charging protocols, and recognition of early thermal distress cues. Research in high-reliability industries highlights the importance of procedural consistency, cross-functional communication, and operator competence in managing technologically

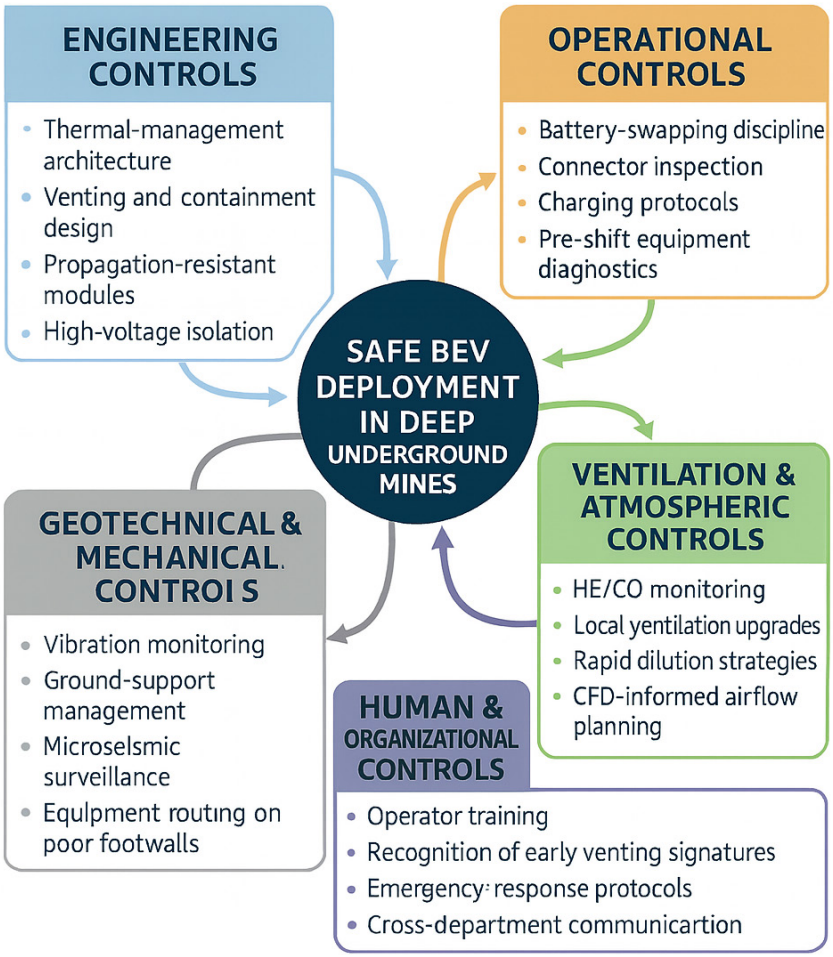


Figure 6. Integrated mitigation framework outlining engineering, operational, ventilation, geotechnical, and human-factor controls required for safe BEV deployment in deep underground mines.

complex systems[19]. Without corresponding adjustments to training, supervision, and safety culture, BEV risks may not be effectively controlled, regardless of engineering sophistication.

These findings collectively indicate that BEV integration must be treated as a mine-wide systems intervention rather than an equipment substitution decision. Electrification influences mine design parameters, including ventilation architecture, traffic flow, equipment placement, geotechnical monitoring, and maintenance schedules. It also impacts organisational processes such as emergency planning, risk communication, and regulatory compliance. The rapidly evolving nature of lithium-ion technologies—shifting chemistries, new pack designs, improved barriers—further requires that risk-management frameworks be dynamic and adaptable.

Finally, the discussion situates BEV risks within broader sustainability and energy-transition imperatives. Electrification remains essential for reducing diesel exhaust, lowering heat loads, and achieving decarbonisation targets. However, responsible implementation requires that the operational and safety implications of BEVs be fully recognised and systematically addressed. Advances in thermal management, diagnostic algorithms, suppression technologies, and pack design will continue to reshape risk profiles. Ongoing research and operational feedback will be necessary to align safety practices with technological evolution.

In sum, BEV deployment in deep underground mining demands a system-level understanding of hazards that integrates electrochemical failure behaviour, operational stressors, ventilation constraints, and human factors. The findings demonstrate that BEV safety cannot be managed through isolated technical fixes but requires coordinated action across design, operations, training, and mine infrastructure in table 3. This systems perspective is essential for enabling safe, efficient, and sustainable electrification of underground mining operations.

6. Limitations and Areas for Further Research

Several limitations constrain the scope and generalisability of this analysis. While the study integrates evidence from electrochemical research, large-scale fire testing, OEM design documentation, and operational observations, it is limited by the absence of full-scale empirical BEV failure

Table 3. Operational and Organisational Controls for BEV Risk Mitigation

Operational and Organizational Controls for BEV Risk Mitigation	
Control Measure	**Description**
Training & Awareness	Educate workers on BEV-specific risks and emergency procedures
Emergency Planning	Develop site-specific incident response and evacuation plans
Pre-Operational Checks	Conduct inspections and diagnostics before shift deployment
Monitoring & Diagnostics	Implement continuous health and performance monitoring
Maintenance Programs	Establish proactive maintenance and repair schedules
Record-Keeping	Maintain logs of BEV operations, incidents, ad maintenance

data from operating mines. Laboratory and module-level tests provide critical insights into venting behaviour, ignition thresholds, and propagation mechanisms, yet underground thermal and ventilation boundary conditions differ substantially from those in test configurations. As a result, quantitative predictions of gas concentrations, propagation rates, or ignition likelihood under real mining conditions require further empirical validation.

Rapid evolution in lithium-ion technologies creates additional uncertainty. The analysis focuses on current NMC formulations, but ongoing shifts toward high-nickel cathodes, silicon-rich anodes, advanced separators, and prospective solid-state architectures are likely to alter degradation, venting, and thermal characteristics. Without a detailed empirical characterisation of these emerging chemistries under mining-relevant stressors, risk models must remain provisional.

Pack-architecture variability limits the ability to generalise propagation behaviour. Cooling-channel geometry, insulation materials, module spacing, structural supports, and venting pathways differ across manufacturers and equipment lines. Without complete engineering schematics or proprietary thermal-performance data, modelling of pack-level behaviour must rely on inference from available empirical studies, which may not capture manufacturer-specific configurations.

Human-factors considerations also require deeper study. Operator recognition of early thermal distress, diagnostic interpretation, adherence to swapping and charging protocols, and response to ambiguous warning states are essential elements of BEV safety. The underground mining context imposes cognitive

and procedural demands distinct from those in surface industrial settings. Empirical research is needed to quantify operator performance under realistic stress and visibility conditions.

Ventilation modelling presents another area requiring expanded research. While this study interprets airflow behaviour through established mining-ventilation principles, predictive analysis of multi-species gas dispersion during BEV venting events requires high-resolution CFD simulations calibrated to mine-specific geometries. Such modelling would improve understanding of how HF, CO, and hydrocarbons migrate through complex networks of drifts, raises, and ramps under variable flow regimes.

Finally, the development of quantitative probabilistic models remains constrained by limited historical failure data. As more mines adopt BEVs and incident-reporting frameworks mature, future research should incorporate statistical methods capable of estimating failure probabilities, exposure distributions, and consequence severities across different operating environments and equipment types.

Despite these limitations, the study provides a comprehensive synthesis of current knowledge about BEV risks in deep underground mining and offers a framework for systematic analysis. Future research should prioritise full-scale underground test programmes, evaluation of next-generation chemistries, human-factors studies tailored to BEV operation, advanced ventilation modelling, and probabilistic risk quantification. These efforts will support the safe and effective evolution of BEV technology within the broader transition to low-carbon mining.

7. Conclusions

The analysis demonstrates that the introduction of BEVs into deep underground mining generates a multidimensional risk environment shaped by the interaction of electrochemical behaviour, mechanical loading, thermal constraints, toxic-gas dynamics, and mine-level operational dependencies. NMC lithium-ion systems, while essential for meeting decarbonization and ventilation-reduction objectives, possess failure pathways that evolve nonlinearly and can escalate rapidly under the confined and mechanically variable conditions characteristic of hard-rock mines.

The evidence shows that duty-cycle volatility, sensor limitations, thermal-management performance, and ambient environmental conditions strongly influence electrical and thermal instability. Mechanical stresses from vibration, uneven ground, and microseismicity contribute directly to latent cell damage and connector degradation, providing credible initiating conditions for failure independent of electrical loads. Early venting generates toxic gases at concentrations that can render headings untenable well before flame onset, and underground airflow behaviour can disperse contaminants unpredictably across the mine.

Propagation behaviour, although mitigated by engineered barriers, remains a significant concern given the confined geometries of underground headings and the sensitivity of barrier performance to thermal gradients, cooling integrity, and pack architecture. BEV immobilisation in a critical airway can disrupt egress, compromise ventilation flows, and escalate localised failures into mine-level emergencies.

Taken together, these findings confirm that BEV risk cannot be addressed through equipment-centric strategies alone. Effective integration requires coordinated system-level approaches incorporating equipment design, ventilation engineering, maintenance practices, geotechnical monitoring, operational protocols, and organisational readiness. Electrification will continue to advance as mines seek reductions in diesel emissions, heat loads, and carbon intensity; however, the safe realisation of these benefits depends on a rigorous understanding of BEV failure dynamics and on the development of resilient, adaptive management frameworks capable of responding to evolving technological and environmental conditions.

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