Identifying the unique risks posed by Thermal Runaway of LIBs in Marine Applications

A Qualitative Risk Assessment of the Hazards in Maritime BESS

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Abstract

The International Marine Organisation(IMO) states that 2.6% of global emissions are released from ships[1] causing a rise in electric marine vessels over the last 20 years, with the greatest adoption in hybrid ferries due to shorter travel times[2]. Currently, **Li-NMC** batteries are a popular option for electric propulsion due to their high specific energy, reduction in fuel consumption and greenhouse gas emissions, as well as improving ship responsiveness and operational performance[2]. However, there are huge drawbacks in **thermal runaway(TR)** issues of the batteries due to large energy demands, which lead to fires, explosions and thermal propagation to adjacent rooms onboard.

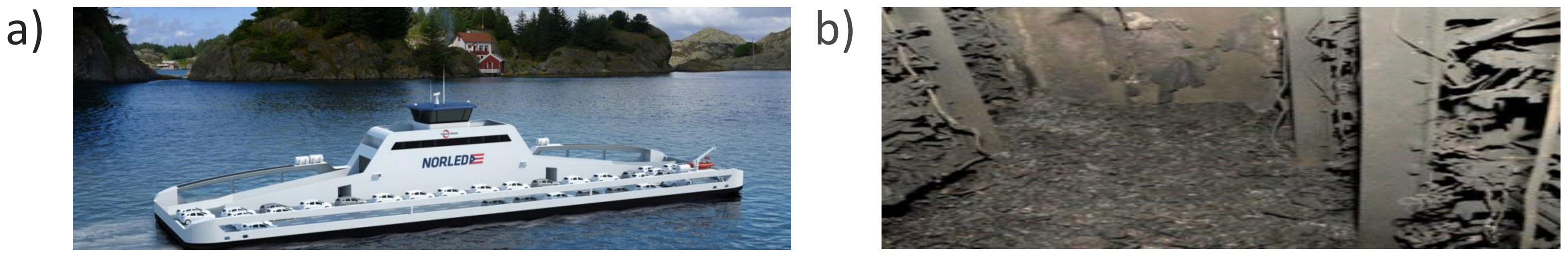

Figure 1: a) The world's first fully electric car ferry, MF Ampere[3] b) MS Brim after a TR catastrophe[4].

Challenges in the Marine Environment

- Accidents such as **MF Ytteroyningen** and **MS Brim** show important risks such as **electrical abuse** of thermally/cyclically unstable cells by overcharging, lack of smooth **BMS interface, BMS coolant leakage** and **gas accumulation** due to the dichotomous issue of closed-space fire extinguishing(e.g. with gaseous NOVEC 1230) to prevent fire propagation, but also simultaneous ventilation of gases to prevent explosion[5].
- Marine batteries show differences to EV and other ESS such as the power needed to support **largely fluctuating ship load profiles[6], seawater/salt air ingression**(causing ISC)**, larger scale** battery space extinguishing/cooling and ventilation, and **complicated emergency response procedures** i.e. need for trained maritime firefighters[5] and difficulty of evacuation of the vessel.

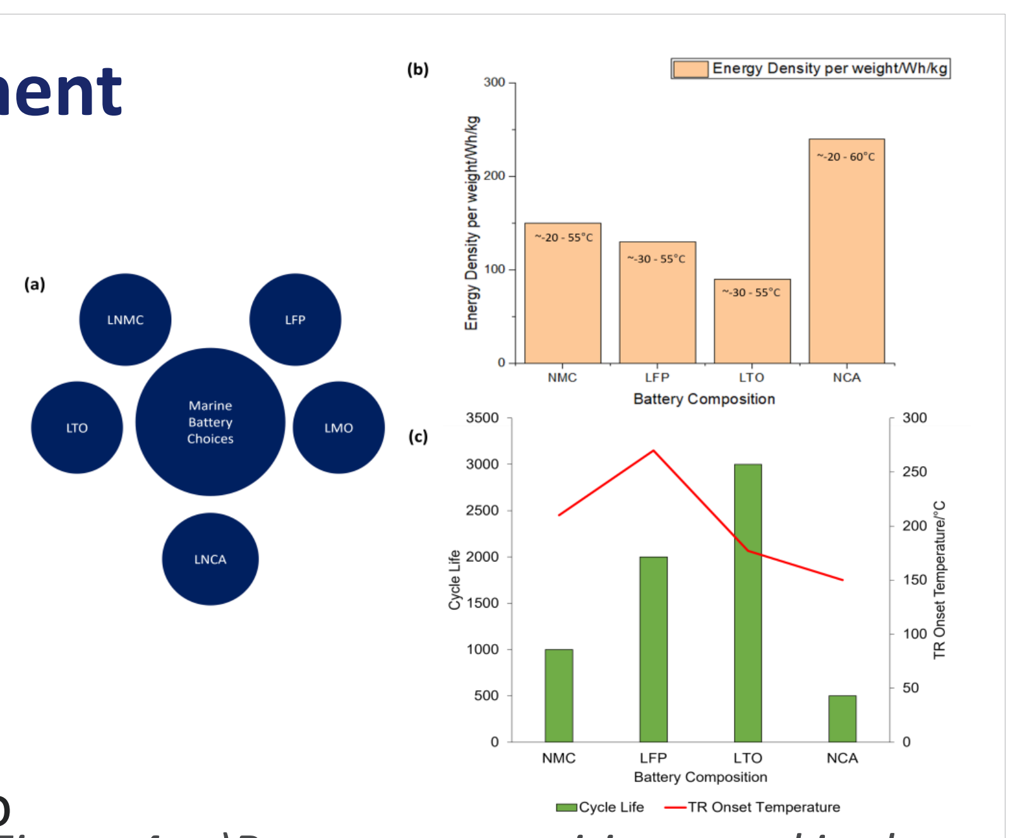

Figure 4: a)Battery compositions used in the marine industry b)energy densities and discharging temperatures c) cycle life and TR onset temperatures[7].

Cause Prevention	TR Propagation Prevention	Gas Spread Prevention
Improvement on watertight nature of room and doors.	Fire-extinguishing capacity of fresh-water based systems increased from 30 → 60mins.	Room and ducts should be gas tight.
Stricter requirements on ventilation ducts and environmental protection of the room.	No requirement for sea-water extinguishing system.	Inlet duct directly from open air and outlet for integrated duct directly to open air.
Minimum of IP44 rating for ingress protection.	Option for combined gas and water spray system for 30mins.	No direct access from public space.
Leakage detection systems.	No requirement for gas system cooling.	3m toxic zones around outlets(no access to any spaces)

Figure 5: TR, fire, explosion and thermal propagation prevention methods set out by the DNV(a marine vessel classification society) in the '1st International Symposium on fire in electric storage at sea[5]'.

Recommendations

- **The Battery System:** Cell chemistry modification, cell/module configurations to limit propagation. Fire protection using **refractory/phase change materials[9,10]**.
- **The Electronic Control System:** Efficient BMS temperature, voltage and SOC monitoring, with considerations of **ISC detection algorithms[8]**. **DC-DC and active front end converters** for better string integration and EMI reduction[11].
- **The Battery Space**: **Location in the stern** rather than collision bulkhead of a ship[11], with **water ingress-rated(IP44)[12]** and **fire protected(A60)** boundaries[13]. High-resolution **off-gas and IR detectors** allowing shutdown when 30% lower flammability limit(LFL) is reached[14]. **Foam-based fire extinguishers** e.g. FIFI4Marine CAFS using **direct injection methods[13]**, or dual combinations of gaseous and water-based(for final flooding operations). **Ventilation ducts** located ≤ 0.4m from the ceiling with high air changes per hour(ACH) extraction fans[15], and **rupture diaphragm discs** at opposite ends of the enclosure[16].

Motivation

- **TR** occurs by: Mechanical, Thermal and Electrical Abuse(most common), causing a series of exothermic reactions and an **internal short-circuit(ISC)**.
- This can have catastrophic effects→ evident in a history of marine accidents.

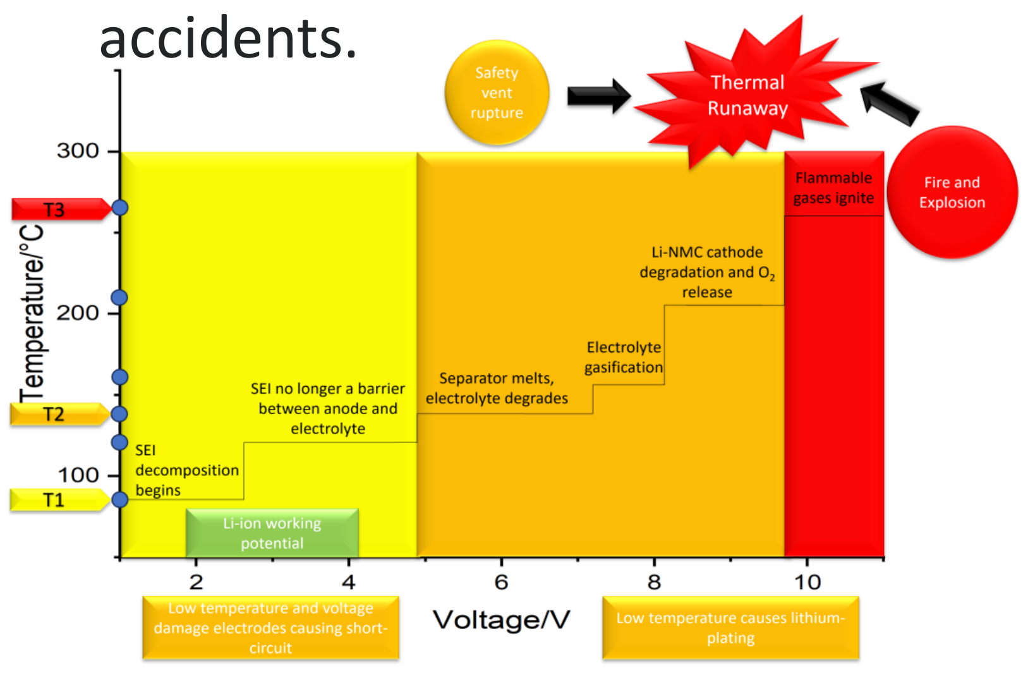

Figure 2: The steps to thermal runaway in a Li-NMC cell.

Methods

- Qualitative risk assessment conducted using Hazard Identification(**HAZID**) and Failure Modes and Effects Analysis(**FMEA**).
- Presented in a **Bow-Tie Diagram** to show threats, barriers, safety measures and consequences.

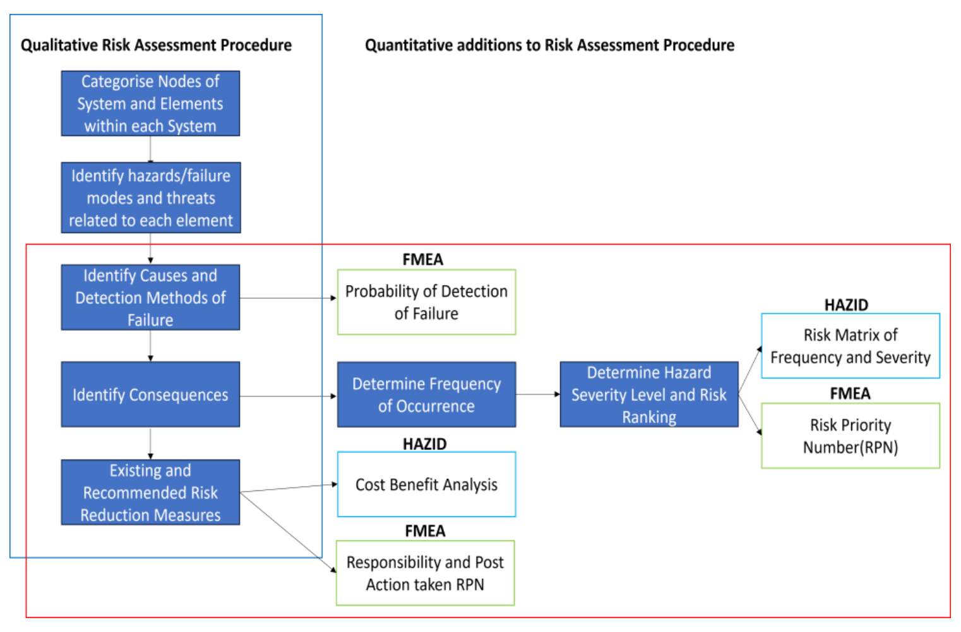

Figure 3: HAZID and FMEA Risk Assessment Flowchart.

Conclusions

- The **Bow Tie Analysis** below shows the causes, barriers to TR, hazard prevention strategies and consequences one of the three abuse conditions: **Electrical Abuse** in **Maritime BESS**, within 3 system nodes: **The Battery System**, **The Electronic Control System** and **The Battery Space**.
- The systems in a marine enclosure are very interdependent and the ambient marine environment can have unpredictable risks, making risk assessments with linear cause and effects redundant → more **holistic** analysis is needed.
- Essentially, we benefit from **'hindsight bias'[17]** as the only learning points for safety engineers are previous accidents.

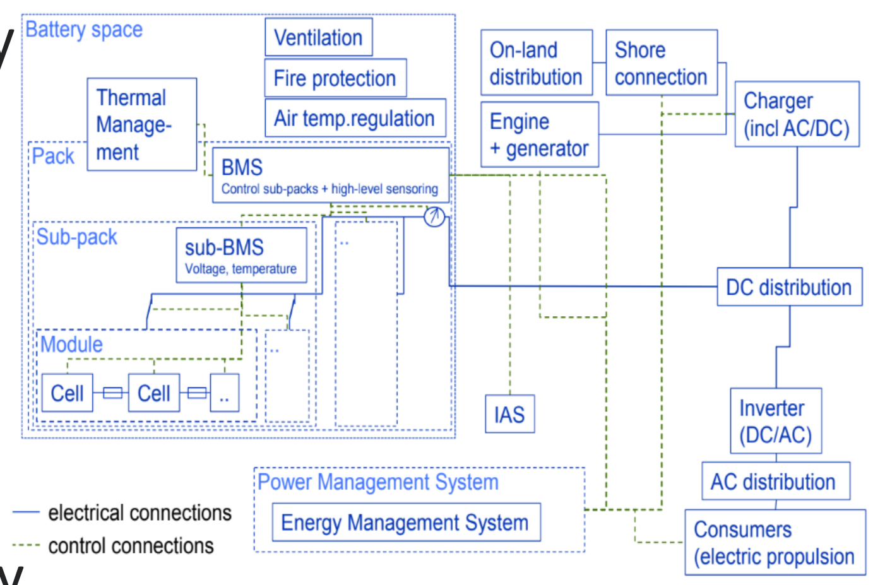

Figure 6: A schematic of Maritime BESS given by the DNV in the 'Guideline for Large Maritime Battery Systems[8]'.

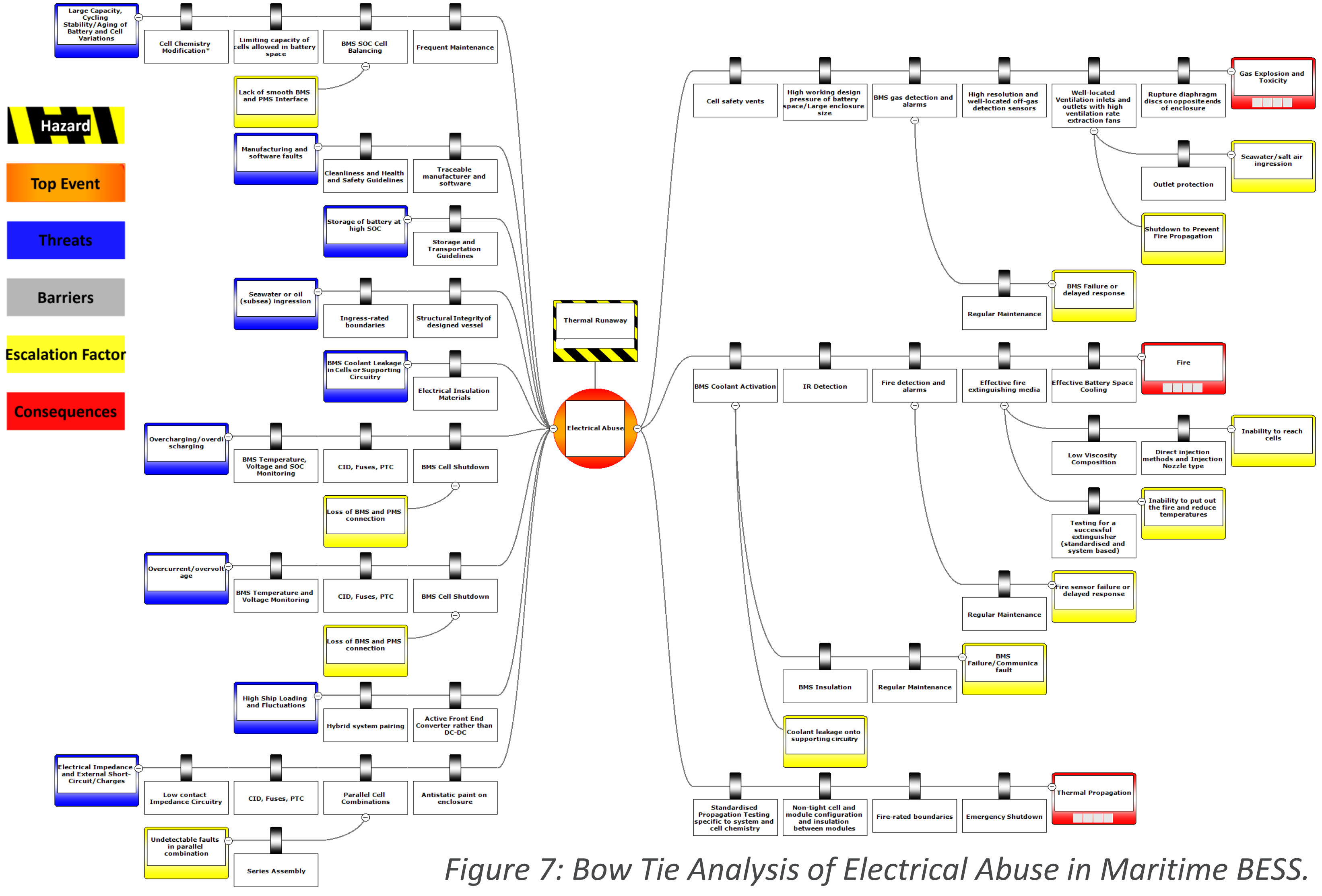

Figure 7: Bow Tie Analysis of Electrical Abuse in Maritime BESS.

Impact / Next steps for Commercialisation

- Early cell barriers need further research e.g. **electrolyte additives** for more stable SEI formation/flame retardance, **solid/ionic electrolytes** to inhibit lithium/copper dendrite growth, **anode and cathode coatings** to improve thermal/structural stability, and **trilayer separators** for higher collapse temperatures[8,9,10].
- Hazards are more easily managed if societies like the **DNV and Lloyd's Register** improve, standardize and integrate systems safely in the BESS e.g. by better BMS integrity, propagation tests on extinguishing media, vent sizes/positioning and sensors- which are dependent on the specific battery chemistry and capacity contained in the room.

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Intern bio

Simran Khanna is a 2nd year Materials Science and Engineering student at Imperial College London, interested in sustainable energy production and storage, and aspiring to join the movement towards Net-Zero. She completed her FUSE internship in the Sol Brown Group at the University of Sheffield.

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