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Risk Assessment and Mitigation Strategy of Hybrid Energy Storage System in 11-m Fully-Electric Seabus

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Abstract**—** Maritime transport is central to global trade but also a significant source of greenhouse gas emissions, which has encouraged the development of Fully Electric Ships (FES) and Hybrid Energy Storage Systems (HESS). By combining LTO and LFP batteries, HESS can lower costs, weight, and volume compared to single-type systems. To ensure these technological advances are implemented safely, early hazard identification methods, such as HAZID, provide a structured approach for detecting potential risks and guiding safer design choices from the outset. This study investigates risk analysis and mitigation strategies for a Hybrid Energy Storage System (HESS) applied to an 11-meter fully electric Seabus, configured with Lithium Iron Phosphate (LFP) and Lithium Titanate Oxide (LTO). The Hazard Identification (HAZID) method is employed to systematically identify potential hazards during operation, covering technical, operational, and environmental aspects. The findings reveal 17 hazards identified in this study; 14 of these are at the ALARP level. The highest-risk hazards include explosion and battery fire, both of which pose severe threats to vessel safety and environmental integrity. To address these critical risks, appropriate mitigation strategies are proposed, including advanced battery management systems, physical protection of critical components, and emergency operational procedures tailored to maritime safety standards. This research highlights the importance of integrating HAZID into the design and operation of HESS to enhance reliability and safety.

Keywords—Batteries, HAZID, HESS, Risk Assessment, Mitigation

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I. INTRODUCTION

Maritime transportation accounts for about 90% of global trade, and the demand for fleets continues to increase. The expansion of sea transport has intensified worries about the resulting greenhouse gas emissions, which have now emerged as a critical challenge for both the industry and the wider society [1]. The concept of the Fully Electric Ship (FES) has been proposed to minimize emissions by replacing conventional diesel engines with a fully electric propulsion system [2]. In practice, single-type, or mono-energy, storage systems are considered the most promising technology because they can be designed as either High-Power (HP) Density or High-Energy (HE) Density. When the focus is on large storage capacity (HE), the size of the Energy Storage System (ESS) will increase, thereby driving a significant rise in initial investment. This challenge has led to the concept of the Hybrid Energy Storage System (HESS), which combines high energy and high power, thereby reducing overall volume, extending lifespan, and lowering the initial installation cost of batteries [3].

The use of HESS by combining two or more battery types may reduce mass, volume, and energy consumption compared with conventional monotype batteries [4][5]. By utilizing a HESS that combines LTO and LFP batteries with optimal configuration, it has been found that this configuration can lower costs by 10.7% and 19.3% compared to single LTO or LFP configurations [6].

Lithium-ion batteries pose significant safety risks mainly due to their heat generation. The use of flammable materials, such as organic electrolytes, separators, and graphite, increases the risk of thermal runaway under abnormal conditions. The confined spaces in battery compartments and the close stacking of batteries make it more likely that a thermal runaway in one cell could set off a chain reaction in others. This can ignite gases released during the process, causing potential explosions within the compartment. Such events not only threaten the vessel's fire safety but also impede the broader adoption of marine energy storage systems and negatively affect public perception [8].

A detailed risk analysis of HESS is crucial for identifying and evaluating technical and operational hazards that may arise throughout the ship's lifecycle. Methods such as Hazard Identification (HAZID), Failure Mode and Effects Analysis (FMEA), and Fault Tree Analysis (FTA) can be used to outline failure scenarios. At the same time, frequency and impact assessments help determine the risk level for each component. The HAZID method is highly effective during the design stage, as it is a proactive, early-phase approach that identifies potential hazards before design is finalized. This enables the implementation of inherently safer designs and prevents significant modifications later in the ship's lifecycle. This makes HAZID the most suitable method for early risk identification. The HAZID for HESS will identify hazards, their causes, consequences, mitigation measures, and appropriate

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preventive actions.

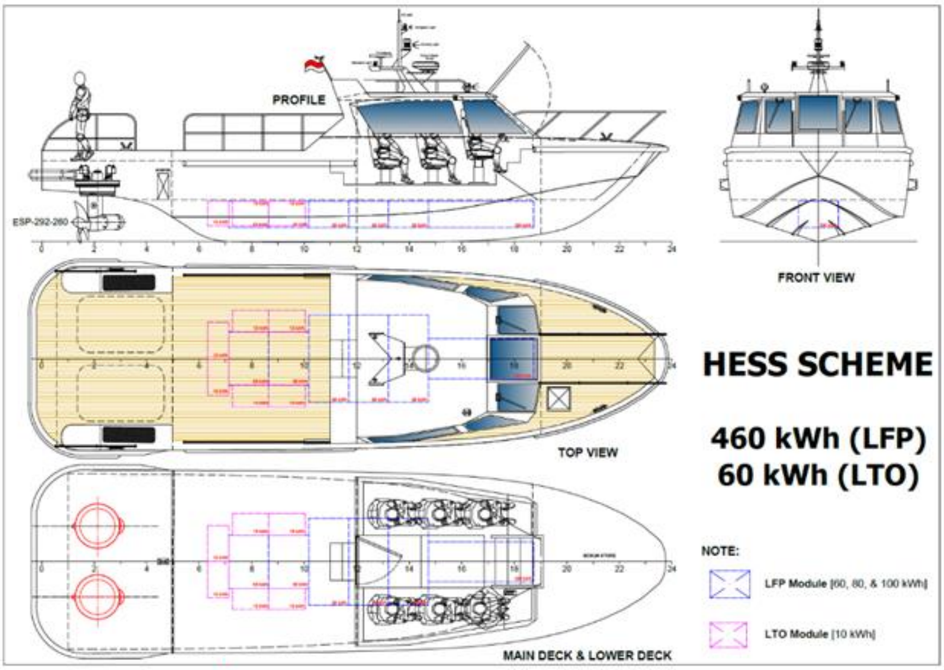

Figure. 1. 11-m seabus HESS installation visualization [10]

In their review, Yin et al. [7] explained that lithium-ion cell failures in the maritime sector are triggered by three types of abuse: mechanical (pressure, impact, puncture, or mechanical deformation), thermal (heat accumulation in containers or battery rooms), and electrical (overcharge, over-discharge, and internal short circuit). Each form of abuse can initiate short-circuit pathways, increase the rate of heat release, and ultimately reach the threshold of Thermal Runaway, which can lead to fire or explosion. Research conducted by P. Bugryniec et al. [8] reported incidents caused by Thermal Runaway between 2012 and 2023, as shown in Table 1. The table outlines the leading causes of failure in electric/hybrid ships, particularly within BESS systems, and their consequences. Table 1 indicates that failures in BESS can result in highly diverse consequences, ranging from smoke development to fire and even explosion.

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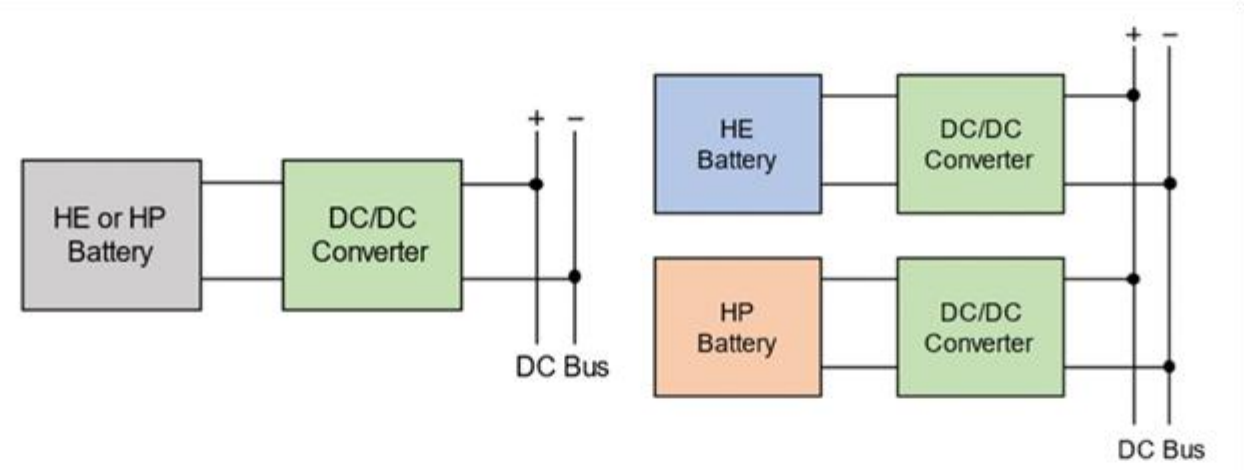


Figure. 2. Schematic battery topology, mono and hybrid [3]

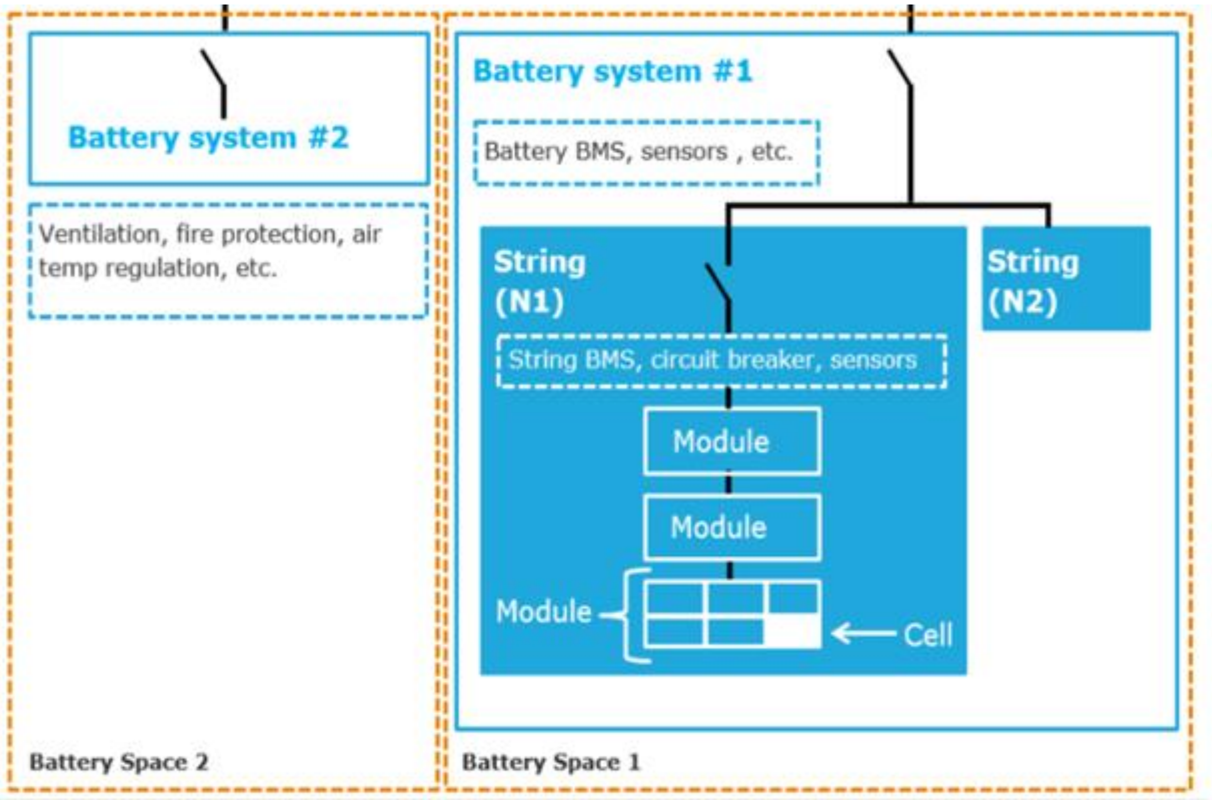


Figure. 3. Battery instalation [9]

Triggering factors such as software errors, coolant leakage, flooding, and short circuits due to overcharging or seawater exposure demonstrate the complex vulnerabilities of shipboard battery systems. The consequences not only cause technical damage but also pose significant safety risks to ship operations and the surrounding environment. To mitigate these risks, international regulatory schemes such as the UN Manual of Tests & Criteria and the IMDG Code require reliability testing (UN38.3), shock-resistant packaging, special labeling, and load limits. Meanwhile, authorities in Norway (NMA), the United States (ABS), and China (CCS/MSA) have issued guidelines on module placement, mandatory BMS systems, as well as recommendations for ventilation and fire protection systems in the battery rooms of electric ships. Methodologically, maritime LIB risk assessment should ideally incorporate Hazard Identification (HAZID) to map hazard scenarios [7].

Several studies have examined potential failures in shipboard BESS systems and their mitigation strategies. Research by P. Bugryniec et al. [8] and the European Maritime Safety Agency [9] provides a comprehensive analysis of various hazards that may arise during BESS operation. These analyses not only highlight technical factors that can trigger failures but also emphasize environmental and operational aspects that increase risks. In addition to identifying potential hazards, both studies present mitigation and prevention measures to reduce the likelihood of incidents. The recommended mitigations include implementing advanced monitoring systems, designing layered protection against the hazard, and establishing clear emergency procedures to address thermal runaway conditions. With these mitigation recommendations, ship operators are expected to improve the reliability of BESS systems while minimizing consequences that could endanger crew safety, passengers, and the surrounding environment.

As the basis for the study, previous research has examined the electrification of supply vessels. In its initial design, the seabus was powered by a conventional diesel engine connected to a waterjet propulsion system. As the first step in the electrification process, the propulsion system was replaced with an azimuthing pod-type propulsion system powered by a lithium-ferro-phosphate (LFP) energy storage system. The study by Haq et al. [10] examined the effects of hybrid energy storage by considering installation costs and weight in a fully electric seabus equipped with an electric propulsion system. The proposed Hybrid Energy Storage System (HESS) configurations included LFP-SC, LFP-LIC, and LFP-LTO to determine the best arrangement that could support seabus operations for 10 years under pulsed propulsion loads. Using a rule-based optimization method, the optimal HESS size for the LFP-LTO configuration was determined, satisfying all weight and cost criteria and constraints. Therefore, this optimized HESS is capable of providing sufficient energy.

II. LITERATURE REVIEW

The application of HESS to an 11-meter fully electric seabus presents complex, multidimensional risks. These risks are not limited to technical aspects of the energy storage system but also extend to impacts on assets, including component and vessel damage; on people, through threats to crew and passenger safety; and on the environment, through potential pollution and disruption of marine ecosystems. The central problem addressed in this study is how to conduct a comprehensive risk analysis to identify and prioritize risks that may occur on the HESS, thereby enabling the formulation of effective mitigation strategies.

TABLE 1.
REFERENCE FOR HESS RISK ASSESSMENT

No	Project Type	Risk Classification	Author	Number of Risk Factors	Risk Factor Identification Techniques
1	Study Electrical Energy Storage for Ships	a. People b. Environment	[9]	18	Hazid Workshop
2	Risk Assessment of marine Li-ion battery energy storage systems	a. People b. Environment	[10]	29	Brainstorming Literature Review
3	Battery Pack Safety Description & Risk Analysis	a. People b. Environment c. Assets	[18]	30	Hazid Workshop
4	Risk analysis of the Lithium Iron Phosphate battery systems and all supporting systems designed for the Full Electric e-PILOT Boat	a. People b. Environment c. Assets	Private Document	37	Hazid Workshop
5	Risk Assessment Using FSA of a Battery-Powered High-Speed Ferry Using		[17]	57	Questionnaire

A. Literature Study

A Battery Energy Storage System (BESS) is an installation that reversibly converts chemical energy into electrical energy and stores it in a rechargeable battery [11]. Related to the HESS system, a component is needed to regulate the load of power distribution using BMS, so that, to carry out its functions optimally, HESS generally consists of the following leading equipment and subsystems:

a) Battery

In battery-based energy storage systems, the structure and hierarchy of components play a critical role in determining performance, flexibility, and ease of maintenance. The following is an explanation of the three main components in a battery system, namely cells, modules, and strings, and their respective functions in the system configuration:

- Cell: A basic electrochemical unit that chemically stores energy and converts it into electricity through a reaction between an anode, a cathode, an electrolyte, and a separator, becoming the core of the battery [9][10].
- Module: a unit consisting of several individual battery cells connected in series or parallel to create a single larger system block, providing higher voltage and energy capacity
- String: a set of battery cells or modules connected in series, designed to achieve a particular voltage level according to the needs of the system.

b) Battery Management System (BMS)

A Battery Management System is an electronic system that manages battery modules and/or packages, performs monitoring, protection, and communication with other systems, and ensures that the battery operates in accordance with predetermined design parameters [14]. These parameters may include voltage, current, temperature, state of charge (SOC), and state of health (SOH). In addition, the BMS regulates the power distribution among batteries, ensuring that each battery's output remains within predetermined limits.

c) DC – DC Converter;

A DC-DC converter is an electronic circuit that converts direct current (DC) from one voltage level to another. In principle, this converter is a power converter that converts the input DC voltage into a different output DC voltage, either higher (step-up) or lower (step-down) than the initial voltage.

d) Battery Thermal Management System (BTMS).

Depending on operating conditions, the battery system can generate substantial heat. On the other hand, batteries are susceptible to high operating temperatures, which can pose safety and performance risks and accelerate degradation. Therefore, many battery systems require a cooling system that typically employs air convection or liquid cooling. Each approach has its own advantages and disadvantages, and the cooling system design must be tailored to the application, battery type, design, and installation location.

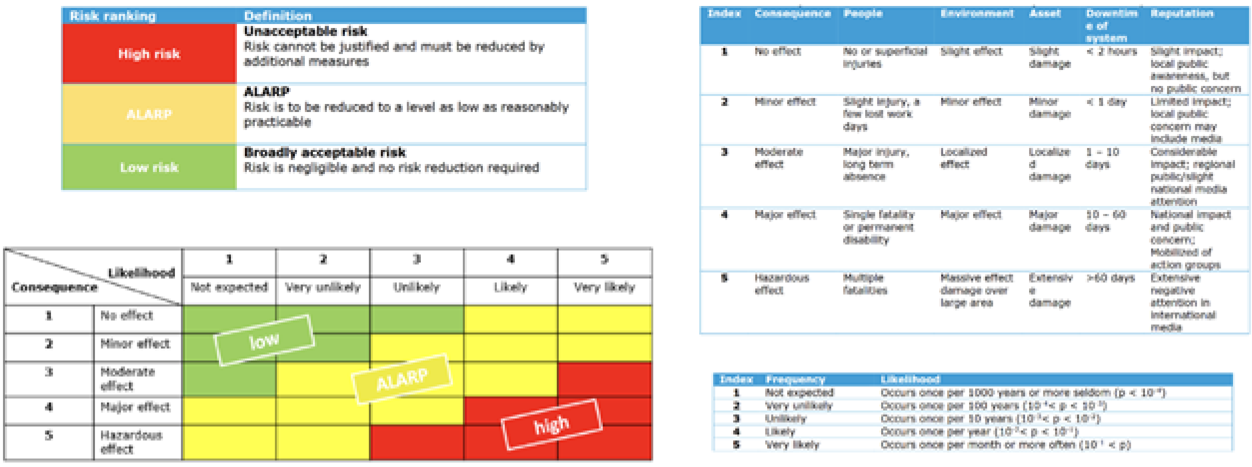
B. Hybrid Energy Storage System

The battery energy storage systems currently used on ships are generally based on a monotype topology, in which a single battery type is used to meet the ship's entire energy and power needs. Based on the application, the battery technology used may be high-power (HP) or high-energy (HE). Battery systems are suitable for providing nominal power sustainably in long-distance shipping, but are less effective at meeting short-term peak power needs. In contrast, HP batteries can handle high power demands, but their low energy density makes them unsuitable for long-term operation. To overcome these limitations, battery hybridization is a practical solution that balances energy and power requirements. HESS systems combine HE and HP batteries (or batteries and supercapacitors) to meet a wide range of operational needs simultaneously. HESS offers several advantages over monotype systems, including lower total investment costs and higher system efficiency [5].

III. METHOD

A. Risk Assessment

Risk assessment is the process of identifying, assessing, and prioritizing potential risks that could impact a project, organization, or system. It helps in understanding uncertainties and making informed decisions to minimize adverse outcomes. The risk assessment process typically involves identifying potential risks, analyzing their likelihood and consequences, and determining appropriate risk management measures. Once risks are analyzed, a risk management strategy can be developed, such as risk avoidance, mitigation, transfer, or acceptance. Risk mitigation involves implementing measures to reduce the likelihood or impact of a risk. The analysis from the risk assessment can often be communicated to the organization to help affected parties understand the factors influencing decisions, based on the ABS Guidance on Risk Assessment [15].



Risk ranking	Definition
High risk	**Unacceptable risk** Risk cannot be justified and must be reduced by additional measures
ALARP	**ALARP** Risk is to be reduced to a level as low as reasonably practicable
Low risk	**Broadly acceptable risk** Risk is negligible and no risk reduction required

Index	Consequence	People	Environment	Asset	Downtime of system	Reputation
1	No effect	No or superficial injuries	Slight effect	Slight damage	< 2 hours	Slight impact; local public awareness, but no public concern
2	Minor effect	Slight injury, a few lost work days	Minor effect	Minor damage	< 1 day	Limited impact; local public concern may include media
3	Moderate effect	Major injury, long term absence	Localized effect	Localized damage	1 – 10 days	Considerable impact; regional public/slight national media attention
4	Major effect	Single fatality or permanent disability	Major effect	Major damage	10 – 60 days	National impact and public concern; Mobilized of action groups
5	Hazardous effect	Multiple fatalities	Massive effect damage over large area	Extensive damage	>60 days	Extensive negative attention in international media

Index	Frequency	Likelihood
1	Not expected	Occurs once per 1000 years or more seldom ($p < 10^{-3}$)
2	Very unlikely	Occurs once per 100 years ($10^{-3} < p < 10^{-2}$)
3	Unlikely	Occurs once per 10 years ($10^{-2} < p < 10^{-1}$)
4	Likely	Occurs once per year ($10^{-1} < p < 10^{-1}$)
5	Very likely	Occurs once per month or more often ($10^{-1} < p$)

Figure. 4. Hazid Risk Matrix [9]

Based on the risk assessment guidelines issued by ABS, the benefits or advantages of using this risk assessment methodology are:

1. Hazard identification and protection
2. Operational improvement
3. Efficient use of resources
4. Rules and regulations development and compliance

The steps for conducting risk assessment are listed below [15]:

a) Identify Risks

Risk identification aims to identify potential hazardous events and scenarios that may occur in the system, including their causes and consequences, and to plan safeguards for prevention and detection to reduce the risk rank and the hazard risk rank [15][16].

b) Risk Analysis

Risk analysis is conducted to determine the risk ranking of potential hazards to the system by assessing the frequency and consequences of each hazard. A single event can have multiple impacts, all of which must be considered in the analysis. The effectiveness of existing protections also needs to be assessed. Frequency and consequences are then multiplied to determine the overall risk level. Depending on the decision-making requirements, a qualitative approach may be sufficient in some cases, while in others, a more detailed quantitative analysis is necessary.

c) Risk Evaluation

Risk evaluation is the process of using the results of a risk analysis to support decision-making, including comparing those results with established risk acceptance criteria. In certain situations, these criteria are defined by regulations or legal requirements. Risk evaluation also determines whether the risk requires mitigation and helps prioritize its management.

d) Risk Treatment

Risk treatment involves selecting one or more options to modify the risk and implementing those options. This process includes assessing whether the residual risk level is acceptable, developing new treatment strategies, and analyzing the effectiveness of the chosen strategy. A well-designed risk management plan should balance costs and implementation efforts with the benefits obtained.

B. HAZID

For the research, data on the results of Risk Assessment using the HAZID Technique were obtained from an ongoing project and from secondary data from other studies, as shown in Table 1 [[8][9][17][18]. Hazard Identification and Risk Assessment (HAZID) is a structured methodology for identifying potential hazards, assessing associated risks, and implementing mitigation measures to enhance safety across industries, including maritime and energy systems. The process involves systematically identifying hazards through brainstorming sessions, expert evaluations, and historical data analysis, followed by qualitative or quantitative risk assessments. This proactive approach enables early detection of safety concerns, allowing preventive measures to be integrated into system design and operational protocols.

Particularly in emerging technologies such as Lithium Iron Phosphate battery systems for electric vessels, HAZID plays a crucial role in ensuring reliability and minimizing operational risks. The benefits of HAZID are substantial, as it improves safety, enhances regulatory compliance, and supports informed decision-making by providing a structured framework for risk evaluation. Early hazard identification reduces the likelihood of accidents, thereby preventing operational disruptions and financial losses.

Risk Matrix

The risk matrix used in this study is based on DNV GL Recommended Practice DNV-RPA203, which serves as a reference for risk analysis. The risk analysis conducted in this study encompasses risks to people, the environment, and assets. Several secondary data sources were used to perform the risk assessment, as shown in Figure 5.

TABLE 2.
LIB CELL REACTION DURING THERMAL RUNAWAY [8]

Temperature (°C)	Reaction Behavior
>80	Degradation of lithium salts and reaction with solvents and Solid Electrolyte Interphase (SEI).
90–130	SEI is damaged, triggering a reaction between the anode and the electrolyte. Produces low heat.
90–230	A lithium-electrolyte reaction occurs, producing gases such as C_2H_4, C_2H_6, and C_3H_6.
120–220	The electrolyte evaporates, resulting in the formation of gases, the pressure on the cell increases. The separator melts at 130°C to 190°C.
160	A significant increase in heat from *self heating* to *Thermal Runaway*. There is a greater release of gases.
200–300	The electrolyte is decomposed. In *Thermal Runaway*, the temperature increases drastically, the decomposed metal oxide cathode produces oxygen. Oxygen oxidizes the electrolyte into CO_2 and H_2O.

TABLE 3.
HAZARD FROM GAS DEVELOPMENT OF LIB [8]

No	**Compound**	***Hazard***
1	Carbon dioxide (CO_2)	Causes headaches, dizziness, confusion, loss of consciousness, and asphyxiation at high concentrations.
2	Carbon monoxide (CO)	Toxic if inhaled, it can damage the fetus, damage organs through prolonged or repeated exposure, and is a highly flammable gas.
3	Hydrogen (H_2)	Highly flammable.
4	Hydrocarbons	Flammable.
5	Hydrogen fluoride (HF)	Fatal if ingested, in contact with the skin, or inhaled; cause severe burns to the skin and eye damage.
6	Hydrogen chloride (HCl)	Causes severe burns to the skin and eye damage; toxic if inhaled; can damage fertility and the fetus; causes respiratory irritation; corrosive to metals; contains pressurized gases.
7	Hydrogen cyanide (HCN)	Fatal if ingested, in contact with the skin, or inhaled; damage to organs through prolonged exposure; highly toxic to aquatic life (long-term effects); very flammable.
8	Nitrogen dioxide (NO_2)	Fatal if inhaled; causes severe burns to the skin and eye damage; may cause or aggravate a fire (oxidizer).
9	Sulfur dioxide (SO_2)	Causes severe burns to the skin and eye damage; toxic if inhaled.
10	Solvents	Liquids and vapors are highly flammable; Highly irritating to the eyes, skin, and respiratory tract.

IV. RESULT AND DISCUSSION

A. HESS *Failure* Risks and Mechanisms

According to the European Maritime Safety Agency [11], the risks and failure mechanisms of batteries, especially lithium-ion batteries, arise from two primary sources: thermal runaway and the release of electrolyte gases that can produce potentially toxic, flammable fumes. In addition, failures in the electrical system, such as short circuits, insulation damage, cable damage, and failures of protection devices, can prevent the system from receiving the required power. Meanwhile, failures in control systems, including the Battery Management System (BMS), can lead to errors in monitoring voltage, current, and temperature, thereby rendering protection strategies ineffective.

a) Thermal *Runaway and Propagation*

The primary risk of lithium-ion batteries during transportation and use is thermal runaway (TR) [19]. Thermal Runaway is a condition in which temperature rises uncontrollably, with the temperature inside the battery components typically exceeding 80 °C or the rate of temperature rise exceeding 1 °C/s, thereby exceeding the battery's heat dissipation capacity. Feng et al. [20] identified two leading causes of thermal runaway in batteries: intrinsic failures and failures resulting from misuse or accidental incidents. The causes of these failures can be further grouped into:

- Mechanical Abuse

Mechanical Abuse occurs when a battery is physically damaged due to impact, fall, penetration, or similar causes.[21]. This condition can damage the separator layer within the battery cell, resulting in an internal short circuit (ISC). As a result, the heat will increase rapidly and can trigger Thermal Runaway.

- Electrical Abuse

Electrical Abuse refers to the misuse of electricity, including internal short circuits, overcharging, excessive current, and overdischarging [12][13]. This situation can disrupt the stability of the electrolyte and electrode, and increase the risk of metal dendrites that can penetrate the separator. Short circuits due to dendrites or current imbalances will result in overheating, which can eventually trigger Thermal Runaway.

- Thermal Abuse

Thermal abuse occurs when a battery is exposed to extreme ambient temperatures, either too high or too low [12][14], or when the cooling system is malfunctioning. Exposure to excess heat can accelerate internal chemical reactions, increase gas pressure, and lower the stability of the electrolyte, which can also make the separator melt. If the temperature exceeds the heat-discharge threshold, the battery will lose the ability to control the temperature rise, thereby triggering Thermal Runaway.

The reaction behavior of lithium-ion batteries is greatly influenced by temperature. Under certain conditions, rising temperatures can trigger chemical changes that may pose safety risks. To understand the reaction stages, the following table presents temperature ranges and the corresponding reaction behaviors. Failure and thermal discharge from a single battery cell are relatively minor threats. However, a greater threat arises when the cell produces sufficient heat that it propagates to neighboring cells, causing thermal runaway in the surrounding cells. When this propagation occurs in the battery system, the generated heat increases exponentially, and the risk of fire involving the battery modules increases. Therefore, battery modules and systems must be designed to prevent intercellular propagation, depending on the cell type used, so that Thermal Runaway is not expected to occur.

b) Gas Release (Gas Development)

In battery-based energy storage systems, one risk to consider is the release of harmful gases. This process typically occurs under abnormal conditions, including thermal runaway, overcharging, mechanical damage, and design and installation failures. The gases released not only pose a threat to human safety but also pollute the environment and may trigger fires or explosions. The gases produced from electrolyte degradation and the battery's internal chemical reactions are often toxic, corrosive, and flammable. Some of them can irritate the respiratory tract, cause tissue damage, and pose long-term health risks. Therefore, identifying the type of gas released is an essential step in risk analysis and mitigation strategies. To provide a clearer picture, the following will present a table of harmful substances that may be released from the battery, along with their main characteristics and effects. This table is intended to serve as a reference for the preparation of comprehensive protection, ventilation, and safety procedures.

c) Electrical and Control System Failures

- Battery Management System (BMS) Failure

Failures in the Battery Management System (BMS) mainly include various essential aspects that can affect the overall performance of the energy storage system, including data asynchrony that causes inconsistent information between modules, communication failures that hinder the exchange of signals between components, acquisition failures that make essential parameters such as voltage, current, and temperature not read correctly, control failures that result in malfunctions of settings distribution of battery operating power, as well as internal and external short circuits in the BMS that can trigger severe damage to pose safety risks. Damage to the BMS can result from interference from other equipment, extreme environmental conditions, damage to connection lines, and software or hardware failures within the BMS.

b. Electrical System Failure

Electrical system failure refers to the failure of electrical connections or protective devices between batteries, including fuse failure, battery connection failure, and aging of the insulation layer. Electrical faults are generally caused by external factors such as extreme environments, mechanical forces, or human error. This failure can cause safety problems in the system or loss of power due to the disconnection of the power distribution system.

c. Fire Extinguishing System Failure

Disturbances in the fire-extinguishing system primarily include alarm failures, failures of the fire-extinguishing operator, and failures of the extinguishing system. Failure of the fire extinguishing system can cause the fire not to be detected in time at an early stage, causing the fire to spread and cause damage to the battery storage system [12]

B. HAZID Worksheet

The hazard is indicated by a number corresponding to the node. The causes, consequences, preventive measures, and mitigating measures are listed in Table 4 of the HAZID worksheet. The post-risk ranking after applying the preventive and mitigating measures is also listed on the worksheet. The consequences are divided by people (P), environment (E), and Assets (A). The hazards are divided into 3 nodes: battery system, battery space, and electrical and control.

a) Battery System
The battery system is the central unit that serves as the primary source of electrical energy. It consists of individual cells and modules carefully arranged to store and deliver power for propulsion, auxiliary equipment, or other onboard systems. Beyond energy storage, the battery system is designed to ensure operational efficiency, reliability, and stability, supported by components that regulate energy flow and protect the cells from damage.

b) Battery Space
The battery space is the dedicated compartment or enclosure where the battery system is installed. This space is engineered to provide structural support, environmental protection, and controlled conditions that safeguard the battery from external influences, including vibration, moisture, and mechanical impact.

c) Electrical and Control
The electrical and control system encompasses all wiring, circuits, sensors, and control units that manage the distribution and regulation of electrical energy. A key component of this system is the Battery Management System (BMS), which monitors charging and discharging, balances cell performance, and prevents unsafe operating conditions. The electrical and control system also integrates the battery with other onboard electrical subsystems, ensuring smooth communication and coordination across the vessel or platform.

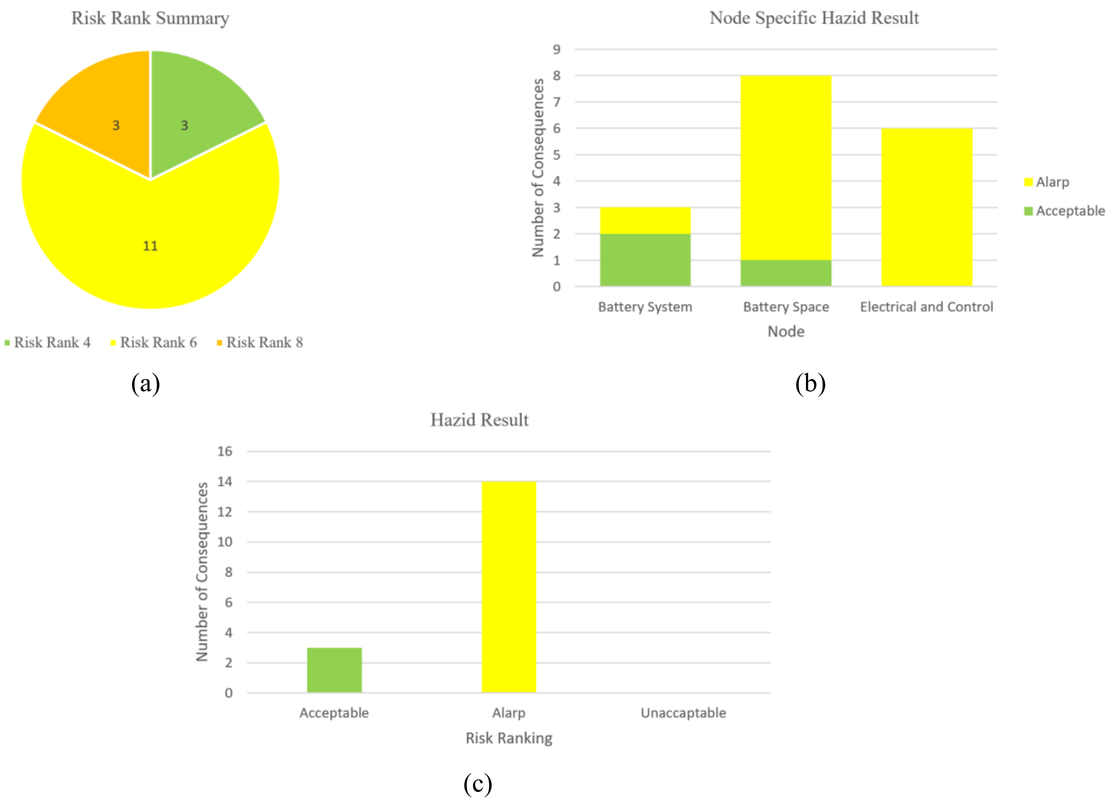


Figure 5. (a) Risk Rank Summary of 11-m Seabus, (b) Node Specific Hazid Result, (c) Summary Hazid Result

TABLE 4.
11-M SEABUS HAZID WORKSHEET

Node No.	Hazard	Cause(s)	Consequence(s)	Safeguard(s)	Post Risk				
					Frequency	Consequences			Risk rank
						P	E	A	
1 Battery System									
1.1	Thermal runaway	-Mechanical abuse: cell(s) - Electrical abuse: -Thermal abuse	- Gas development (flammable, toxic, corrosive) - High temperature - Potential fire - Potential Explosion - Thermal runaway propagation to another cell/module - Battery Degradation - Loss of battery power	- Battery Management System has voltage, current, and temperature monitoring and alarm, and is also able to calculate and track the SoH of each cell in the system. - Battery module enclosures and battery module racks are designed to prevent thermal events from propagating to adjacent cells and modules (cell/module-level thermal runaway isolation) - Battery thermal management system and integrated cooling of the heat sink enclosure on each module - Class rules require a fire-suppression system in the battery room - Operating Procedure - Battery system has an emergency shutdown - Integrated exhaust system in the rack	2	2	2	2	4
1.2	Gas generation	Cell, module, and system Thermal runaway failure	- Asphyxia - Potential fatalities to personnel entering the room - Potential Fire - Potential Explosion - Toxic environment - Loss of battery power	- Battery Management System has voltage, current, and temperature monitoring and alarm, and is also able to calculate and track the SoH of each cell in the system. - Ventilation in battery space for gas removal - Battery system has an emergency shutdown - Gas sensor in the room, increasing ventilation, or shutting down the system upon detecting gas below LEL - Explosion-proof rated ventilation extraction fan	3	2	2	2	6
1.3	Thermal runaway propagation	Thermal runaway failure	- Gas development (flammable, toxic, corrosive) - High temperature - Potential fire - Potential Explosion - Thermal runaway propagation to another cell/module - Battery Degradation - Loss of battery power	- Battery Management System has voltage, current, and temperature monitoring and alarm, and is also able to calculate and track the SoH of each cell in the system. - Battery module enclosures and battery module racks are designed to prevent thermal events from propagating to adjacent cells and modules (cell/module-level thermal runaway isolation) - Battery thermal management system and integrated cooling of the heat sink enclosure on each module - Class rules require a fire-suppression system in the battery room - Operating Procedure - Battery system has an emergency shutdown - Integrated exhaust system in the rack	2	2	2	2	4

CONTINUED TABLE 4.
11-M SEABUS HAZID WORKSHEET

Node No.	Hazard	Cause(s)	Consequence(s)	Safeguard(s)	Post Risk				
					Frequency	Consequences			Risk rank
						P	E	A	
2 Battery Space									
2.1	Gas accumulation	- Failure of the exhaust ventilation fan - Lactation of ducts - Blockage of exhaust - Ventilation system mechanical damage	- Gas accumulation in the battery space (flammable, toxic, corrosive) - Potential fire - Potential Explosion - Asphyxia - Potential fatalities to personnel entering the room	- Vent openings at different heights for heavier-than-air gases - Function test - Battery system has an emergency shutdown - Recommendation of a vent pipe system for piping of gases to open air or an alternate safe location	3	2	2	2	6
2.2	Fire	-Thermal runaway, Module Thermal runaway propagation, -Ignited flammable gas generation	- High temperature - Severe Gas generation, including flammable and toxic species - Total system failure - Loss of vessel - Potential Fatalities - Potential explosion	- Class rules require a fire-suppression system in the battery room - Battery Management System with an alarm to the operator in case of high temperature in the battery room - Thermal barriers - Battery system has an emergency shutdown - Explosion-proof rated ventilation extraction fan - Dilution with CO2 or N2 - Fireproof insulation	2	4	4	4	8
2.3	Explosion	Ignited gas generation	- Total system failure - Loss of vessel - Loss of the battery system - Potential Fatalities - Potential Explosion	- Class rules require a fire-suppression system in the battery room - Battery Management System with an alarm to the operator in case of high temperature in the battery room - Thermal barriers - Battery system has an emergency shutdown - Explosion-proof rated ventilation extraction fan - Dilution using CO2 or N2 - Fireproof insulation - Enhanced room ventilation to the external environment for gas removal	2	4	4	4	8
2.4	External fire	Fire in adjacent rooms	- Battery room temperature increase that may cause overheating of the battery - Battery system damage	- Temperature and smoke detector in the battery room with alarm - Fireproof insulation between rooms - Firefighting in the adjacent space of the battery room - Independent ventilation system for the battery room - Cooling system limiting the overtemperature of the battery system - Battery system has an emergency shutdown	3	2	2	2	6

TABLE 4.(CONTINOUS)
11-M SEABUS HAZID WORKSHEET

Node No.	Hazard	Cause(s)	Consequence(s)	Safeguard(s)	Post Risk				
					Frequency	Consequences			Risk rank
						P	E	A	
2.5	Fire was not detected and extinguished	- Failure of the fire suppression system - Pump failure - Reignition - Temperature/Gas sensor failure - Alarm Ignored	- Fire spreads between racks - See 2.2	- Periodic function tests - Fire extinguishing method tested before installation - Redundant sensor - Battery system has an emergency shutdown	2	4	4	4	8
2.6	Fire not detected	- Sensor failure - Alarm ignored - Slow response	- Fire spreads between racks - Loss of the battery system - Loss of room/vessel	- Periodic function tests - Redundant sensors - Train personnel on LIB TR behaviour - IR sensors - Fast response sensors - Frequent maintenance	1	4	4	4	4
2.7	Structural failure	- Collision - Grounding - Design/installation error	- Mechanical impact to the battery system leading to thermal runaway (See 1.1)	- Proper commissioning nd service procedures - Battery system has an emergency shutdown	2	3	3	3	6
2.8	Water in the battery room	- Sea water ingress through improperly placed/designed in/outlets - Condensation of water from cold sea air in the warm battery room - Structural damage, water penetration from the above deck - Damaged water piping - Damage to water-based fire suppression	- Corrosion - Short circuits - Electrolysis of salt water, H2 and Cl2 gas generation	- Watertight Bulkheads in Battery Room - Battery connection plate IP56 rated - Battery cartridge is IP67 - Bilge alarm for inside battery room - Bilge suction system in the battery room	3	2	2	2	6
3. Electrical and Control									
3.1	BMS and PMS failure	- Operational error - Communication failure - BMS or PMS hardware failure - Wire defect - Mechanical damage	- Loss of local control - Loss of power due to the limited power distribution of the HESS failure	- System tested and verified - Follow the operating procedure - Electrical system protection	2	3	1	3	6
3.2	Converter failure	- Operational error - Mechanical abuse - Component failure of BMS/PMS	- Loss of local control - Loss of power due to the limited power distribution of the HESS failure	- System tested and verified - Follow the operating procedure - Electrical system protection	2	2	1	3	6
3.3	Emergency shutdown system failure	- Operational error - Communication failure - Component failure of BMS/PMS - Wire defect - Mechanical damage	- Loss of local control - Loss of power due to the limited power distribution of the HESS failure	- System tested and verified - Follow the operating procedure - Electrical system protection	2	2	1	3	6

TABLE 4.(CONTINOUS)
11-M SEABUS HAZID WORKSHEET

Node No.	Hazard	Cause(s)	Consequence(s)	Safeguard(s)	Post Risk				
					Frequency	Consequences			Risk rank
						P	E	A	
3.4	Master battery unit screen failure	- Impact - Power Peak - Fuses damage	- Loss of local control - Loss of power due to the limited power distribution of the HESS failure	- System tested and verified - Follow the operating procedure - Protection system - Battery Management System is in operation anyway - The Energy Management System can still be controlled - The Energy Management System screen works as the Master can still be controlled	2	2	1	3	6
3.5	Multiple Battery Basic Unit Controller Failure (PS or SB Side)	- Impact - Power Peak - Fuses damage	- Loss of control of a single battery cartridge	- System tested and verified - Follow the operating procedure - Protection system - Each string has its own Master Battery Unit and is redundant to the others - Battery Basic Unit will be isolated - Battery Management System will raise an alarm	2	2	1	3	6
3.6	Communication Failure between BMS and EMS	Wire defect	- Loss of control of a single battery cartridge	- System tested and verified - Follow the operating procedure - Electrical system protection	2	2	1	3	6

The hazards that may occur on the 11-meter Seabus are, in general, quite similar to those encountered on other vessels, encompassing risks related to navigation, structural integrity, and operational safety. The risk ranking is determined by multiplying the frequency of occurrence by the severity of the consequences, with the highest consequence value being used as the basis for calculation. This approach ensures that hazards with both high likelihood and severe outcomes are prioritized in the overall risk assessment.

In the Hazid, 17 hazards are identified: 3 at the battery system node, 8 at the battery space, and 6 at the communication and control. These hazards are shown in Figure 5(b). According to the risk rank summary in Figure 5(a), the HAZID results are divided into three risk levels: 4, 6, and 8. This distribution provides a clear overview of HESS's overall risk profile. Specifically, three hazards are classified as risk rank 4, indicating a relatively low risk that is usually manageable with standard safety measures. Most hazards (11) fall under risk rank 6, while three are categorized at rank 8. Although rank 8 has a higher value than rank 6, both fall within the ALARP (As Low as Reasonably Practicable) principle, indicating similar risk management approaches are required. Hazards in these ranks are significant and require careful monitoring, mitigation strategies, and strict safety protocols to manage risks. The occurrence of hazards across both ranks underscores the need for consistent preventive measures, stronger safety systems, and operational controls to reduce the likelihood of hazards and mitigate their potential impacts. Overall, the distribution indicates that no hazards are deemed unacceptable; however, the predominance of ALARP-level risks underscores the need for comprehensive, uniform risk management across ranks 6 and 8 to ensure safety and operational reliability.

By applying this method, critical hazards such as fire, explosion, and undetected, unextinguished fires can be systematically identified as having the highest risk rank (a risk rank point of 8), thereby requiring immediate attention and the implementation of safeguard measures. Explosion hazards can arise from ignited gases, but several measures are in place to mitigate this risk. Class rules require the installation of a fire-suppression system in the battery room and a Battery Management System with an alarm to provide early warnings of high temperatures. Thermal barriers limit heat transfer, and the battery system includes an emergency shutdown feature to prevent escalation. Explosion-proof ventilation fans safely remove gases, and dilution with CO_2 or N_2 reduces concentrations. Fireproof insulation provides additional protection, and effective room ventilation directs gases outside for safe venting. Together, these measures create a comprehensive safety approach that reduces the likelihood and impact of explosions [8][9][10][24][25][26].

However, what sets this vessel apart is the integration of the Hybrid Energy Storage System

(HESS), which introduces additional layers of complexity that demand special attention. With the adoption of HESS, the electrical and control systems become critical aspects that must be carefully monitored and managed, as they directly influence the reliability and safety of the ship's operations. Unlike conventional systems, the integration of high-energy and high-power storage technologies requires precise coordination among components, advanced monitoring systems, and robust protective measures to prevent failures such as thermal runaway, overload, or control malfunctions.

In particular, hazards within the electrical and control systems must be emphasized, as failures in Battery Management Systems (BMS), Power Management Systems (PMS), converters, or emergency shutdown mechanisms can lead to electrical abuse, overheating, or even loss of control over battery units. These risks underscore the importance of redundancy, insulation between modules, continuous monitoring of voltage, current, and temperature, and clear emergency procedures. The presence of such hazards necessitates system verification, strict adherence to SOPs, and proactive testing to ensure safe operation [8][9][10][27][28].

These challenges highlight the importance of conducting detailed hazard identification and risk assessments during the design and operational phases, ensuring that preventive measures are embedded early in the system architecture. Ultimately, while the Seabus shares many hazards with other vessels, the unique risks associated with HESS, particularly in the electrical and control systems, demand a more comprehensive and proactive safety approach to ensure both operational efficiency and the protection of crew, passengers, and the surrounding environment.

V. Conclusion

Based on the HAZID analysis of the HESS system, hazards have been identified across all levels of the system, including the battery system, battery space, and electrical and control systems. A total of 17 hazards were identified in this study. In addition, the causes of failure and the mitigations required to reduce risks have also been identified. These findings highlight the importance of conducting detailed hazard identification and risk assessments during the design and operational phases, ensuring that preventive measures are embedded early in the system architecture. The hazards are categorized as 3 at acceptable risk and 14 at ALARP risk. Battery fire, explosions, and undetected or unextinguished fires have a risk rank of 8. The electrical and control systems are also crucial, as they form the backbone of monitoring, regulation, and safe operation of the HESS. They oversee the flow of electricity, identify anomalies, and deliver real-time feedback via alarms and sensors. Ultimately, while the Seabus shares many hazards with other vessels, the unique risks associated with HESS, particularly in the electrical and control systems, demand a more comprehensive and proactive safety approach to ensure both operational efficiency and the protection of crew, passengers, and the surrounding environment

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