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Utilizing ANP for a Comprehensive Risk Assessment and Mitigation Prioritization of Lithium Battery Energy Storage Systems (LBESS) on Commissioning Service Operation Vessels (CSOV)

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Abstract

Integrating Lithium Battery Energy Storage Systems (LBESS) into offshore Commissioning Service Operation Vessels (CSOV) poses significant safety concerns, including fire, explosion, and toxic gas release. The expanding offshore wind industry increases demand for CSOVs equipped with energy storage, making robust risk management essential. This study addresses the critical need to understand and manage LBESS hazards on CSOVs, given the absence of comprehensive international regulations and inherent lithium battery risks like thermal runaway. This study utilizes Risk Assessment data and the Analytic Network Process (ANP) to analyze these hazards and identify optimal mitigation strategies. The research systematically identified six distinct hazards, eighteen main causes, and twenty specific sub-causes through hazard identification (HAZID). A purposive sampling method selected seven qualified practitioners with at least three years of experience in BESS security and risk assessment on CSOVs, including ship construction supervision. Data was collected via a questionnaire using pairwise comparisons and the Saaty scale, processed with Super Decisions software, and combined using Geomean calculations. The ANP analysis shows safety is the top priority for LBESS implementation (63.6%), significantly exceeding environmental (16.3%) and operational (10.2%) factors. Within safety, explosion (39.0%) and fire (25.9%) are the most prevalent hazards, with thermal runaway and battery electrolyte decomposition being key contributors to LBESS failure. For mitigation, the analysis highlights Battery Physical Design and Protection (31.5%), Battery Monitoring and Control Systems (27.9%), and Operational Procedures and Training (15.4%) as crucial. Prioritizing safety is essential for LBESS deployment on CSOVs, with explosion and fire being the most severe threats, and robust engineering and operational protocols are critical mitigation strategies.

1. Introduction

The Offshore Wind Farm industry began in 1991 off the coast of Vindeby, Denmark, with a turbine capacity of 459 KW, and has since grown significantly, particularly in Europe [1] [2]. Driven by market growth in Europe and initiatives like the UK's Green Industrial Revolution (targeting 50 GW of offshore wind power by 2030), the European Commission, in collaboration with countries such as Germany, Netherlands, Denmark, and Belgium, has committed to increasing capacity to 60 GW by 2030 and 300 GW by 2050. The Offshore Wind Farm sector has also expanded rapidly in Asia, with China leading at 19.7 GW, surpassing the UK's 12.2 GW in 2021. The offshore wind investment will increase dramatically, reaching 50% of total blue economy investment by 2050, driving demand for specialized vessels [1] .

This research focuses on Commissioning Service Operation Vessels (CSOVs), ships specifically designed for modern offshore wind farm operations. These vessels are equipped with specialized tools and systems to improve maintenance efficiency and support for wind turbines. CSOVs often include an energy storage system (ESS), such as the approximately 750 kWh system described, which typically consists of a battery room, converter, and management system. Such systems must comply with regulations like DNV-GL RU-SHIPS Pt. 6 Ch. 2 Sec. 1. Figure 1 illustrates a CSOV vessel with its gangway in operation. There are several main activities and main operational modes carried out by CSOV-type vessels, which will be related to the performance of the installed LIBESS, such: transfer personnel to the wind turbine transition section, transfer spare parts via bridge or crane, hotel for technicians, Operations center for maintenance planning, Warehousing and transportation of tools and equipment for offshore wind.

Figure 1. Illustration of a CSOV vessel with Gangway in operation [3]

This ship is equipped with several units of power generation equipment, one of which is LIBESS, installed on the tank top of the ship:

- 2 units of generators with a capacity of 1,700 KW.
- 2 generator units with a capacity of 940 KW.
- 1 unit emergency generator with a capacity of 274 KW.
- Energy Storage System (ESS) with Lithium Battery with a total capacity of 745 KW.

Lithium Battery Energy Storage System on CSOV Vessel.

The shipping industry is transitioning to carbon-neutral fuels, with increasing adoption of alternative fuel propulsion and battery energy storage systems (BESS). The use of BESS on ships has significantly increased, with over 800 battery-operated vessels, primarily in Europe [1]. However, there's a lack of international regulations governing the safety of battery use on ships, relying instead on class requirements and industry standards. Lithium Battery Energy Storage Systems (LBESS) are in demand for their efficiency and emission reduction potential, but they also pose fire risks [4] [5] [6]. This paper focuses on understanding and managing the hazards of LBESS on Commissioning Service Operation Vessels (CSOVs) through risk analysis. It aims to assess fire risk levels using an integrated approach and evaluate effective mitigation strategies to improve the safety of CSOV operations using LBESS, contributing to the broader knowledge of LBESS risks in the maritime industry.

Understanding the complexities of LBESS risks is paramount; for instance, Zhang (2023), in 'Fire Accident Risk Analysis of Lithium Battery Energy Storage Systems during Maritime Transportation,' specifically investigated fire and accident risks in maritime LBESS using Fault Tree Analysis (FTA) and Bayesian Network Analysis, aiming to provide a deeper understanding of risk factors and fire accident probabilities to inform mitigation and enhance safety [7] . Similarly, Yin (2023) provided a comprehensive overview of LIB risks in marine transport and ship power, discussing safety challenges from mechanical, electrical, and thermal abuse, and highlighting research gaps in current safety management and regulations, particularly concerning thermal runaway. [4]

Recent research highlights significant gaps in large-scale energy storage system safety. For instance, a study employing the Improved Risk Assessment Approach and Event-Centric Systemic Analysis (EcS) Method identified insufficient detail in safety subsystem assessments (detection, fire suppression, emergency ventilation) and a lack of failure mechanism analysis in safety risk assessments, potentially leading to hazardous conditions from unintended system actions [8]. Complementing this, a comprehensive review of lithium-ion battery fire suppression methods analyzed existing literature, publications, and testing studies to identify trends and gaps in suppression technology, offering insights and recommendations for further research [9]

The electrochemical energy storage systems, particularly BESS (Flow, lead-acid, sodium-ion, nickel-based, and lithium-ion batteries), are predominantly used for short-term storage (minutes to days) [10]. Lithium-ion battery fire safety is a key challenge for BESS development [11] [6] [9]. While lithium-ion batteries offer excellent energy and power density, they present safety vulnerabilities. Failure categories include battery faults, sensor faults, and actuator faults. Critical lithium-ion battery failures that can lead to thermal runaway include overcharging, overheating, electrolyte leakage, and external/internal short circuits [12][13] [14] [15] [16] [17].

Identified research gaps include focus on lithium-ion batteries may limit the scope for other lithium battery types and specific applications, limited experimental data or case studies may result in over-reliance on theoretical analysis, lacking empirical evidence on fire suppression performance, emerging suppression technologies may not be fully explored, and regulatory aspects of lithium-ion battery fire safety and suppression may receive insufficient attention.

Identify and prioritize the key criteria, hazards, and mitigation strategies associated with Lithium Battery Energy Storage Systems (LBESS) on Commissioning Service Operation Vessels (CSOVs) through expert elicitation and the application of the Analytic Network Process (ANP) using SuperDecision software. This involves understanding which factors (safety, economic, operational, environmental), dangers (fire, explosion, etc.), and risk reduction methods are considered most important by experienced professionals in the field.

Examining over 750 commercial marine BESS installations [18]. It offered practical guidance on installation feasibility, associated risks and costs, and operational performance on vessels like OSVs and cruise ships, also advocating for further research in enhancing safety measures. The research advocates for "enhancing safety measures" in "further development" but don't delve into the specific technical failure mechanisms (like thermal runaway, battery electrolyte decomposition, mechanical damage, manufacturing faults) and their relative contributions to overall risk.

2. Method

Risk assessment is a crucial tool for decision-making. By analyzing the risks associated with various options, like those pertaining to finances, health, safety, and the environment, it provides essential information. This information is vital for making sound choices and clarifying the decision at hand. As Figure 2 illustrates, the teams conducting this risk analysis use a specific flow method to determine these risks. The results of risk assessments can also be communicated within an organization to ensure stakeholders understand the factors influencing the decision. [19]

In this research, the author uses documents that have been released by the designer and battery supplier from a CSOV shipbuilding project in 2024. In this case, the author uses data from the risk assessment that has been reviewed and discussed by expert teams in their respective fields. In determining hazards, this research refers to the Handbook-maritime-offshore-battery-systems, published by DNV-GL in 2016, as the data source for the previous project. In paragraph 5, the safety assessment steps, scope, and list of potential hazards in LIBESS are explained. Hazards in LIBESS can be related to Lithium Batteries, Battery Systems, and the environment. [20]

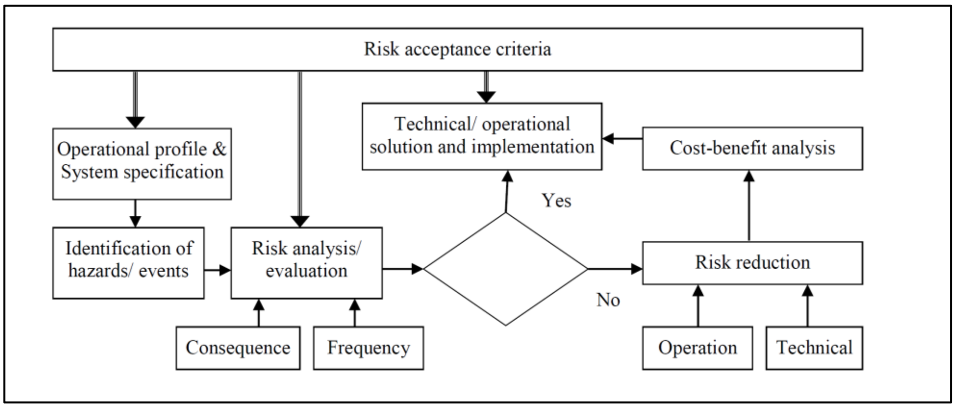

Figure 2. The team's working method in determining risk analysis

From the hazard identification (HAZID) that has been previously organized, the author categorizes, summarizes and marks the results, as shown in Figure 3. This study systematically identified six distinct hazards (Fire, Explosion, Toxic, Electrical Hazards, Erroneous human intervention, and Environmental Hazards). To thoroughly analyze these, eighteen main causes were categorized, ranging from various types of fires and explosions to toxic leakages and electrical shocks. Further detailed investigation led to the identification of twenty specific sub-causes, including factors like over-voltage, electrolyte decomposition, mechanical abuse, and latent cell defects, providing a comprehensive framework for risk assessment

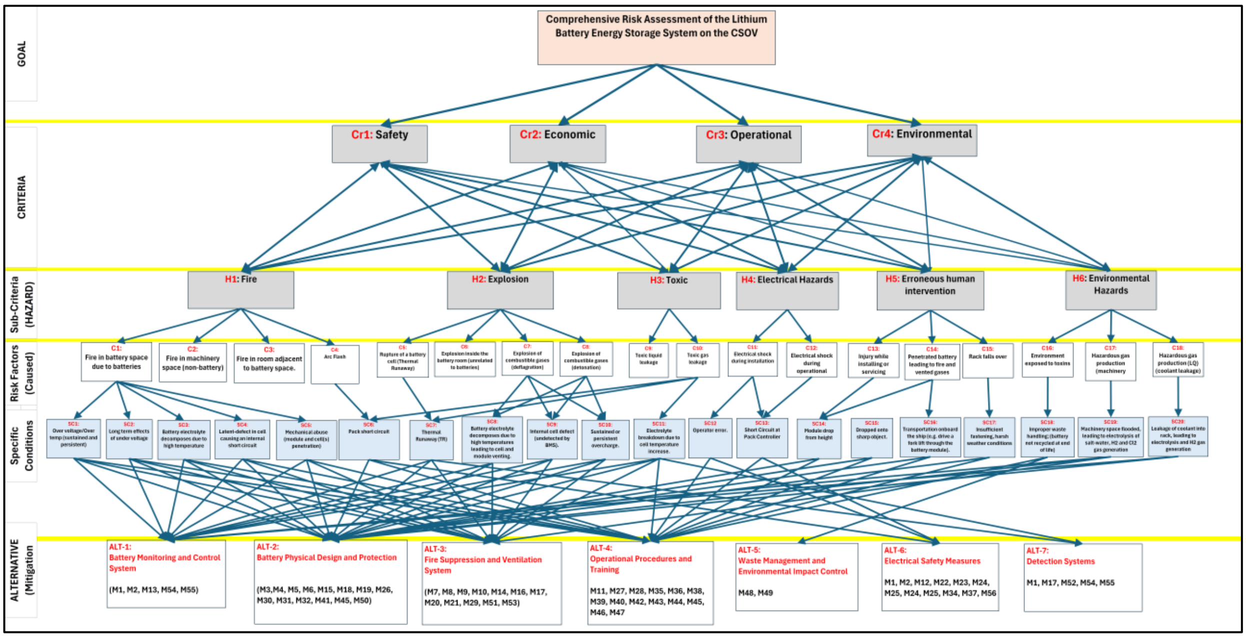

Figure 3. Comprehensive Risk Assessment Hierarchy for Lithium Battery Energy Storage Systems on CSOVs using ANP

The mitigation measures for the safe use of lithium batteries were categorized using methods such as battery thermal safety monitoring, battery thermal management systems, and fire extinguishing techniques and fire protection systems [15]. Subsequently, another journal discussed several aspects implying strategies to enhance safety and efficiency, which can be considered forms of risk mitigation or challenges. These include the development and implementation of energy management systems, the application of battery management systems, the use of safer lithium-based battery technology and design, and strict regulations [21].

In this study, the categorization of 56 mitigation alternatives carried out to reduce hazards was simplified by the author into 7 mitigation categories (ALT): Battery Monitoring and Control System, Battery Physical Design and Protection, Fire Suppression and Ventilation System, Operational Procedures and Training, Waste Management and Environmental Impact Control, Electrical Safety Measures, and Detection Systems. This categorization is also based on relevant safety engineering principles and industry practices related to Battery Energy Storage Systems (BESS), in addition to several literatures from previous research [15] [21]. These categories cover various important aspects in BESS risk management, ranging from physical design and protection to operational procedures and detection systems. The purpose of this categorization is to facilitate analysis and decision-making in selecting the most effective mitigation strategies.

ALT-1: Battery Monitoring and Control System.

This category focuses on mitigation strategies related to battery monitoring and control systems. Alternatives in this category include actions such as the implementation of advanced Battery Management Systems (BMS), the use of sensors to detect abnormal conditions, and the development of control algorithms to prevent undesirable events.

a. M1: BMS detects over-voltage and over temperature and uses hardware-based interrupt loop to stop current prior to thermal runaway.
b. M2: Hardware -based over-voltage and over temperature safety (redundant to BMS).
c. M13: Corvus battery module enclosures (metal) and battery module racks are designed to prevent thermal events from propagating to adjacent cells and modules.
d. M54: Leak sensor in the base of each rack, connected to BMS.
e. M55: Ground fault detection at BMS.

ALT-2: Battery Physical Design and Protection.

This category focuses on the physical design of batteries and protection against physical damage. Alternatives in this category include the use of fire-resistant materials, robust battery module designs, and the implementation of insulation systems to prevent thermal propagation.

a. M3: Corvus battery module enclosures (metal) and battery module racks are designed to prevent thermal events from propagating to adjacent cells and modules.
b. M4: Cell-level thermal runaway isolation (passive elements only); proven under Norwegian Maritime Authority.
c. M5: Module enclosure and thermal design results in large thermal time constant value for module.
d. M6: Corvus specifies/utilizes flame retardant materials.
e. M15: Rack and module enclosures provide double layer of metal protection on all sides except module front (which has thick metal face).
f. M18: Rack, modules, and all external surfaces are metal and flame retardant.
g. M19: Thermal mass of ESS necessitates that an external fire would have to be unsuppressed and sustained for extended period of time in order to present a risk to the battery modules.
h. M26: Rack design (shorts cannot be created within the rack, due to module installation pattern.)
i. M30: Integrity of the equipment enclosures will protect the modules and pack controller.
j. M31: Power and communication cables are contained and protected within the rack.
k. M32: Rack and module protection.
l. M41: Enclosure protection (metal).
m. M45: Structural analysis of racking.
n. M50: Racking has no liquid pooling capabilities at location of busbars or cables.

ALT-3: Fire Suppression and Ventilation System.

a. M7: Integrated air cooling of heat sink enclosure on each module.
b. M8: Integrated exhaust system in rack.
c. M9: Module pressure relief (burst disk) venting into rack exhaust system.
d. M10: Recommendation of vent pipe system that allows piping gases to open air or alternate safe location.
e. M14: Class rules require fire-suppression system in the battery room.
f. M16: Fire suppression in room. The other equipment in the same machinery space will define the fire suppression needs and likelihood for that space. The ESS will not increase the overall fire risk level due to the ventilation piping for any escaped gases.
g. M17: Inlet air temperature sensors. Pack cooling fans (integrated) to be stopped in the event of external fire to prevent heating of heat sink and cells.
h. M20: In the event of eventual cells and modules venting, escaping gases are exhausted to integrated ventilation piping system within the racking.
i. M21: Fire outside the battery space will first be solved by fire suppression system in that location, and secondarily by the fire suppression in the battery room (if the fire breached the battery room bulkheads.)
j. M29: Over-pressure relief is vented into ventilation system. This design is verified by testing.

k. M51: Number of systems plumbing joints minimized.
l. M53: Coolant will drain to rack base and be contained.

ALT-4: Operational Procedures and Training.

a. M11: Energy management system complies with maker guidelines.
b. M27: Service Procedures.
c. M28: Training.
d. M35: Procedures for commissioning and service.
e. M36: Appropriate PPE Safety training of personnel.
f. M38: Training for customer personnel for every system.
g. M39: Use lifting equipment during installation and follow installation procedure.
h. M40: Use PPE to prevent pinching.
i. M42: "Dangerous goods" packaging, with proper labeling
j. M43: Use lifting equipment during installation and follow installation procedure.
k. M44: Foundation to be approved by class (if weigh above 50 kN).
l. M45: Structural analysis of racking.
m. M46: Commissioning procedure.
n. M47: Design requirements for installation.

ALT-5: Waste Management and Environmental Impact Control.

a. M48: Recycling facilities available.
b. M49: "Green passport"/IHM to be made.

ALT-6: Electrical Safety Measures

a. M1: BMS detects over-voltage and over-temperature and uses hardware-based interrupt loop to stop current prior to thermal runaway.
b. M2: Hardware -based over-voltage and over-temperature safeties (redundant to BMS).
c. M12: Pack contactors and fuses rated for full load.
d. M22: External short circuits are protected by the fuses in Pack Controller.
e. M23: Battery connections are at the back of the rack (contained) and at a distance from the operators (reducing the incident energy exposure).
f. M24: Connections are factory tested and not user serviceable.
g. M25: Pack connections in rack base require Pack/battery removal so there is no battery energy available for Arc Flash. External energy sources are still available and must be locked out.
h. M34: All connections at the rear of the battery module.
i. M37: Power cables not accessible during operation.
j. M56: Majority of coolant connections in area segregated from the electrical connections.

ALT-7: Detection Systems

a. M1: BMS detects over-voltage and over-temperature and uses hardware-based interrupt loop to stop current prior to thermal runway.
b. M17: Inlet air temperature sensors. Pack cooling fans (integrated) to be stopped in the event of external fire to prevent heating of heat sink and cells.
c. M52: Validation leakage test verifies no interaction between coolant and current carrying elements.
d. M54: Leak sensor in the base of each rack, connected to BMS.
e. M55: Ground fault detection at BMS.

The Analytic Network Process (ANP). ANP is a new, broader, and deeper form of the Analytic Hierarchy Process (AHP) developed by Saaty [22] [23]. AHP is a comprehensive method that can address a wide range of multi-objective, multi-actor, and multi-criteria problems, even for uncertain decisions with different alternative numbers [24] [25]. Although AHP addresses many shortcomings of other MCDM techniques, it does not consider the possibility of dependencies among different elements and assumes factors independently. This assumption is not accurate in some internal and external environmental effects [26]. These issues should be based on a network system with functional dependencies that allow feedback between clusters and high-level factors depending on low-level clusters [22].

The study on risk assessment and risk management in shipbuilding indicates that safety measures are based on the level of risk. The system and equipment, such as the battery system, have risks that can be managed to prevent damage and operation. However, it is crucial to address all risks with clear and accurate information. The Hazard Identification (HAZID) study, conducted for the installation of LBESS in CSOV, is important for developing the ANP model in this research. The HAZID methodology identifies hazards such as fire, explosion, toxic, electrical, and environmental hazards. Main causes include fires in battery space, explosions in machinery space, arc flashes, thermal runaway, explosions, combustible gas explosions, liquid leakage, electrical shocks, injuries, contaminated battery, rack falls, toxins, hazardous gas production, and coolant leakage. Sub-caused causes include over voltage, over temperature, battery electrolyte decomposition, internal cell defects, operator errors, and machinery space flooding. The 7 ALT category of alternative mitigation strategies, based on industry principles and practices, covers various aspects of BESS risk management, from design and physical analysis to operational procedures and detection systems.

In this study, the sampling method used is purposive sampling. Purposive sampling is a non-probability sampling technique in which the researcher selects samples based on certain predetermined characteristics or criteria [27]. In the context of this research, the established criteria are Practitioners with a minimum of 3 years of experience in the field related to security and risk assessment of BESS on CSOV, with one of the following specific roles: Supervision of LIBESS Ship Construction and Having experience in supervising or being directly involved in the shipbuilding process using lithium-ion battery energy storage systems (LIBESS). This includes an understanding of the integration of the BESS system into ship design, installation, testing, and commissioning.

Based on these criteria, the researcher will identify and select 7 qualified practitioners to be respondents in this study. This sample size is considered adequate to ensure the validity and reliability of the data collected, given the specific expertise required and the complexity of the issues being studied (Saaty, 2008).

The data collection method used in this research is through a questionnaire. The questionnaire is designed based on the developed ANP structure (Figure 3), which consists of objectives, criteria, sub-criteria, and mitigation alternatives. Each question in the questionnaire consists of pairwise comparisons, where respondents are asked to assess the relative importance between two ANP elements using the Saaty scale (1-9).

This questionnaire is used to collect subjective data from practitioners regarding their preferences and assessments of various ANP elements. This data is then processed using Super Decisions software to generate priority weights for each mitigation alternative. (Figure 4). To combine assessments with various experts, this study uses Geomean calculations. Geomean is a type of average that is useful for combining values with different scales or units and is less sensitive to extreme values compared to the arithmetic meaning.

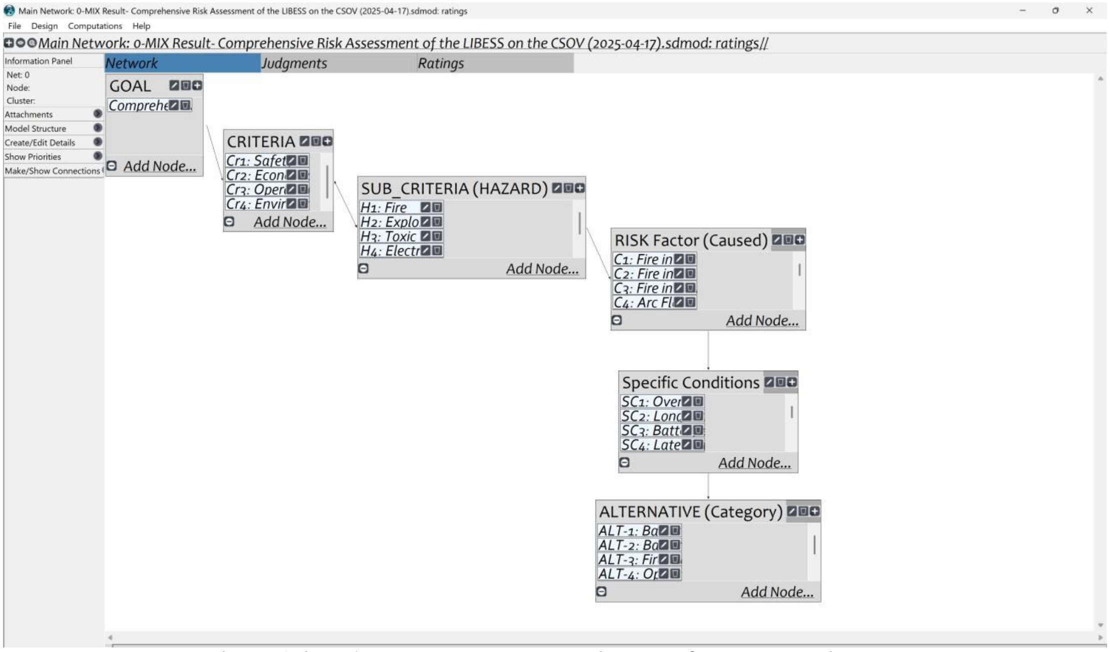

Figure 4. Network Model in the Super Decision application for LBESS Risk Assessment on CSOV

3. Results and Discussion

The study focuses on the importance of safety, economic, operational, and environmental factors in a project's risk management, using Super Decision, a method from the Analytic Network Process (ANP) found that safety is the most important factor in risk management, with a higher priority given to safety. However, there are variations in other criteria between the different stakeholders, indicating a difference in perspective and experience. The study also used the Geomean approach to determine the importance of safety, resulting in a higher priority for Cr1: safety with 64%, followed by Cr2: economics 16 %, and Cr4: environmental factors 10%, as shown in Figure 5-a.

These results indicate that in the context of LBESS on CSOVs, safety is paramount, likely driven by the severe consequences associated with battery failures such as explosions and fires. The high priority assigned to physical design, protection, monitoring, and control underscores the need for robust engineering solutions to prevent and manage these critical hazards. The lower emphasis on economic factors suggests that the immediate safety and operational integrity of the system are considered more important than cost optimization. Furthermore, the recognition of operational procedures and training highlights the role of human factors in mitigating risks, indicating that even with advanced technology, proper handling and emergency response protocols are essential. Expert consensus on various hazards, as depicted in Figure 5-b, places Explosion (H2) as the top priority at 39%, with Fire (H1) (26%) and Toxic (H3) (15%) following. This highlights the paramount importance of developing robust mitigation measures against explosion and fire.

No Icon	Cr1: Safety		0.63639	0.044249
No Icon	Cr2: Economic		0.09810	0.006821
No Icon	Cr3: Operational		0.10240	0.007120
No Icon	Cr4: Environmental		0.16311	0.011341

(a)

No Icon	H1: Fire	0.25933	0.036063
No Icon	H2: Explosion	0.39033	0.054279
No Icon	H3: Toxic	0.15277	0.021244
No Icon	H4: Electrical Hazards	0.08557	0.011900
No Icon	H5: Erroneous human intervention	0.04663	0.006485

(b)

Figure 5. Judgment Result: Analytic Network Process (ANP) Hierarchy of Criteria (a) and Hierarchy of Hazard (b)

As shown in Figure 6, the cause analysis consistently prioritizes Thermal Runaway (SC7) as the foremost sub-cause of LBESS failure, reflecting its perception as the most significant threat. Battery Electrolyte Decomposition due to high temperatures (SC8) and Short Circuit at Pack Controller (SC13) are also deemed significant priorities, a pattern consistent with recent lithium battery safety studies. The safety issues related to Lithium Batteries, particularly thermal runaway (TR) and its propagation, have not found robust solutions. This has hindered the current development and application of Lithium Batteries. The main causes of thermal runaway in Lithium Batteries were examined from three main triggering factors, including mechanical abuse, electrical abuse, and thermal abuse [16]. A crucial factor limiting the massive use of lithium-ion batteries is their potential safety hazards. Thermal runaway causes batteries to generate Joule heat and heat from chemical side reactions. This heat is then transmitted to adjacent batteries at the module and pack level, leading to the spread of thermal runaway. Chemical reactions inside the battery also release a large amount of toxic and flammable gases at high temperatures. Ultimately, the release and combustion of these gases can pose more significant hazards [17].

No Icon	SC1: Over voltage/Over temp (sustained and pers~	0.06220	0.006900
No Icon	SC2: Long term effects of under voltage	0.02046	0.002270
No Icon	SC3: Battery electrolyte decomposes due to high t~	0.05815	0.006451
No Icon	SC4: Latent-defect in cell causing an internal~	0.03313	0.003675
No Icon	SC5: Mechanical abuse (module and cell(s) penet~	0.03313	0.003675
No Icon	SC6: Pack short circuit	0.06407	0.007108
No Icon	SC7: Thermal Runaway (TR)	0.16230	0.018005
No Icon	SC8: Battery electrolyte decomposes due to high t~	0.14923	0.016555
No Icon	SC9: Internal cell defect undetect by BMS	0.05745	0.006373
No Icon	SC10: Sustained or persistent overcharge	0.05956	0.006608
No Icon	SC11: Electrolyte breakdown due to cell te~	0.05268	0.005844
No Icon	SC12: Operator error.	0.05363	0.005950
No Icon	SC13: Short Circuit at Pack Controller	0.05363	0.005950
No Icon	SC14: Module drop from height	0.03897	0.004323
No Icon	SC15: Dropped onto sharp object	0.00000	0.000000
No Icon	SC16: Transportation onboard the ship (e.g. d~	0.00780	0.000865
No Icon	SC17: Insufficient fastening, harsh weather~	0.01169	0.001297
No Icon	SC18: Improper waste handling; (battery not r~	0.02683	0.002977
No Icon	SC19: Machinery space flooded, leading to elec~	0.03380	0.003750
No Icon	SC20: Leakage of coolant into rack, leading to el~	0.02130	0.002363

Figure 6. Judgment Result: Analytic Network Process (ANP) Hierarchy of Sub-caused

Super Decision analysis, incorporating the judgment of seven experts, identified Battery Physical Design and Protection (ALT-2) as the top-priority mitigation strategy for LBESS risks on CSOVs, commanding 32%. This was closely followed by Battery Monitoring and Control Systems (ALT-1) at 28%, and Operational Procedures and Training (ALT-4) at 15%, as detailed in Figure 7.

While individual expert opinions showed some variation for alternatives like Fire Suppression and Ventilation Systems (ALT-3) and Electrical Safety Measures (ALT-6), the combined results (Figure 7) underscore a consensus on the critical role of robust physical design, comprehensive monitoring, and thorough operational protocols in mitigating LBESS risks on CSOVs. Lower prioritization of Waste Management and Environmental Impact Control (ALT-5) and Detection Systems (ALT-7) suggests their perceived lesser impact on primary risk reduction.

Icon	Name	Normalized by Cluster	Limiting
No Icon	ALT-1: Battery Monitoring and Control System	0.27915	0.030968
No Icon	ALT-2: Battery Physical Design and Protection	0.31548	0.034999
No Icon	ALT-3: Fire Suppression and Ventilation System	0.12497	0.013864
No Icon	ALT-4: Operational Procedures and Training	0.15371	0.017052
No Icon	ALT-5: Waste Management and Environmental Impact~	0.01341	0.001488
No Icon	ALT-6: Electrical Safety Measures	0.06907	0.007663
No Icon	ALT7: Detection Systems	0.04420	0.004904

Figure 7. Judgment Result: Analytic Network Process (ANP) Hierarchy of Alternative Mitigation Strategies

4. Conclusion

This study employed an integrated assessment with the Analytic Network Process (ANP) to critically evaluate the risks associated with Lithium Battery Energy Storage Systems (LBESS) on Commissioning Service Operation Vessels (CSOVs). The findings unequivocally establish safety (63.6%) as the paramount priority for LBESS implementation, significantly outweighing environmental (16.3%) and operational (10.2%) considerations. Specifically, the ANP analysis rigorously identified explosion (39.0%) and fire (25.9%) as the most prevalent and severe hazards. The research further specifies Thermal Runaway (16.23%) and Battery Electrolyte Decomposition due to high temperatures (14.92%) as key contributors to LBESS failure. The study conclusively demonstrates that effective mitigation hinges on three critical areas: Battery Physical Design and Protection (31.5%), robust Battery Monitoring and Control Systems (27.9%), and comprehensive Operational Procedures and Training (15.4%). These results provide a data-driven framework for prioritizing safety measures and developing resilient engineering and operational protocols, directly informing stakeholders on crucial strategies for safe and sustainable LBESS integration within the offshore wind industry.

While a consensus exists on these top safety priorities, lower prioritization of economic factors suggests a risk-averse approach. Varying expert opinions on other criteria, hazards, and lower-ranked mitigation (e.g., Environmental Hazards, H6) reveal the inherent complexity of risk assessment, indicating areas for future exploration. To further enhance these findings, future research should delve into the rationale behind expert views through qualitative studies, integrate empirical data via incident analysis and quantitative risk models (e.g., FMEA), and conduct cost-benefit analyses of prioritized mitigation strategies to confirm their practical and economic feasibility.

References

[1] "European Maritime Safety Agency (EMSA), *Guidance on the Safety of Battery Energy Storage Systems (BESS) on Board Ships*, Lisbon, Portugal, Nov. 2023. [Online]. Available: https://emsa.europa.eu/publications/inventories/download/7643/5061/23.html

[2] Y. Chen and H. Lin, "Overview of the development of offshore wind power generation in China," *Solar Energy*, vol. 239, Oct. 2022. doi: https://doi.org/10.1016/j.seta.2022.102766.

[3] B. Li, "Operability study of walk-to-work for floating wind turbine and service operation vessel in the time domain," *Ocean Engineering*, vol. 220, Jan. 2021. doi: https://doi.org/10.1016/j.oceaneng.2020.108397.

[4] R. Yin, M. Hu, J. Luo, X. Wu, Y. Yang, and Y. Xu, "Risk analysis for marine transport and power applications of lithium-ion batteries: A review," *Process Safety and Environmental Protection*, vol. 181, pp. 266-293, Jan. 2024. doi: https://doi.org/10.1016/j.psep.2023.11.015.

[5] DNV GL, *DNVGL-RU-SHIP Part 6 Chapter 2: Propulsion, Power Generation and Auxiliary Systems*, Oslo, Norway, 2015. [Online]. Available: http://www.dnvgl.com

[6] H. Helgesen, *Maritime Battery Safety Joint Development Project: Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression Partner Group*, DNV GL, Oslo, Norway, 2019. [Online]. Available: http://www.dnvgl.com

[7] C. Zhang, H. Guo, Z. Cheng, X. Liang, J. Yuan, and Z. Li, "Fire accident risk analysis of lithium battery energy storage systems during maritime transportation," *Sustainability*, vol. 15, no. 19, Oct. 2023, Art. no. 14198. doi: https://doi.org/10.3390/su151914198.

[8] E. H. Y. Moa and Y. I. Go, "Large-scale energy storage system: safety and risk assessment," *Sustainable Energy Research*, vol. 10, no. 1, Sep. 2023. doi: https://doi.org/10.1186/s40807-023-00082-z.

[9] M. Ghiji, L. Luo, R. Rao, and J. Wang, "A review of lithium-ion battery fire suppression," *Energies*, vol. 13, no. 19, Oct. 2020, Art. no. 5117. doi: https://doi.org/10.3390/en13195117.

[10] Asian Development Bank, *Handbook on Battery Energy Storage System*, Manila, Philippines, Dec. 2018. doi: https://doi.org/10.22617/TCS189791-2.

[11] J. A. Jeevarajan, T. Joshi, M. Parhizi, T. Rauhala, and D. Juarez-Robles, "Battery hazards for large energy storage systems," *ACS Energy Letters*, vol. 7, no. 8, pp. 2725-2733, Jul. 2022. doi: https://doi.org/10.1021/acsenergylett.2c01400.
[12] O. Grönlund, M. Quant, M. Rasmussen, O. Willstrand, and J. Hynynen, *Guidelines for the Fire Protection of Battery Energy Storage Systems for Safe Transport*, Division Safety and Transport, Borås, Sweden, 2020.
[13] P. J. Bugryniec, E. G. Resendiz, S. M. Nwophoke, S. Khanna, C. James, and S. F. Brown, "Review of gas emissions from lithium-ion battery thermal runaway failure – Considering toxic and flammable compounds," *Journal of Energy Storage*, vol. 95, May 2024, Art. no. 111288. doi: https://doi.org/10.1016/j.est.2024.111288.
[14] M. Kaliaperumal, S. Paramasivam, N. Shanmugasundaram, and K. Kalimuthu, "Cause and mitigation of lithium-ion battery failure – a review," *Materials*, vol. 14, no. 19, Oct. 2021, Art. no. 5676. doi: https://doi.org/10.3390/ma14195676.
[15] M. Zhi, L. Chen, Y. Zhao, and K. Wang, "Review of prevention and mitigation technologies for thermal runaway in lithium-ion batteries," *Aerospace Traffic and Safety*, vol. 1, no. 1, pp. 55-72, Mar. 2024. doi: https://doi.org/10.1016/j.aets.2024.06.002.
[16] X. Hu, Q. Liu, X. Fang, Y. Liu, and L. Zhang, "Advancements in the safety of lithium-ion battery: The trigger, consequence and mitigation method of thermal runaway," *Chemical Engineering Journal*, vol. 470, Feb. 2024, Art. no. 148450. doi: https://doi.org/10.1016/j.cej.2023.148450.
[17] J. E., H. Xiao, S. Tian, and Y. Huang, "A comprehensive review on thermal runaway model of a lithium-ion battery: Mechanism, thermal, mechanical, propagation, gas venting and combustion," *Renewable Energy*, vol. 223, Aug. 2024, Art. no. 120762. doi: https://doi.org/10.1016/j.renene.2024.120762.
[18] W. He, H. Zhou, Z. Tang, and Y. Liu, "Lessons learned from the commercial exploitation of marine battery energy storage systems," *Journal of Energy Storage*, vol. 87, May 2024, Art. no. 111440. doi: https://doi.org/10.1016/j.est.2024.111440.
[19] T. Zhu, S. Haugen, and Y. Liu, "Risk information in decision-making: definitions, requirements and various functions," *Journal of Loss Prevention in the Process Industries*, vol. 72, Sep. 2021, Art. no. 104572. doi: https://doi.org/10.1016/j.jlp.2021.104572.
[20] DNV GL, *Qualification of Large Battery Systems: DNV GL Handbook for Maritime*, Oslo, Norway, 2016. [Online]. Available: http://www.dnvgl.com
[21] A. Aksöz, B. Asal, S. Golestan, M. Gençtürk, S. Oyucu, and E. Biçer, "Electrification in maritime vessels: reviewing storage solutions and long-term energy management," *Applied Sciences*, vol. 15, no. 10, p. 5259, May 2025. doi: https://doi.org/10.3390/app15105259.
[22] H. Taherdoost and M. Madanchian, "Analytic network process (ANP) method: A comprehensive review of applications, advantages, and limitations," *Journal of Data Science and Intelligent Systems*, vol. 1, no. 1, pp. 12-18, May 2023. doi: https://doi.org/10.47852/bonviewjdsis3202885.
[23] T. L. Saaty and M. Hall, *Fundamentals of the Analytic Network Process*, Pittsburgh, PA, USA: RWS Publications, 2001.
[24] M. R. Asadabadi, E. Chang, and M. Saberi, "Are MCDM methods useful? A critical review of Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP)," *Cogent Engineering*, vol. 6, no. 1, Jan. 2019, Art. no. 1623153. doi: https://doi.org/10.1080/23311916.2019.1623153.
[25] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao, "Review on multi-criteria decision analysis aid in sustainable energy decision-making," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 9, pp. 2263-2278, Dec. 2009. doi: https://doi.org/10.1016/j.rser.2009.06.021.
[26] S. Kheybari, F. M. Rezaie, and H. Farazmand, "Analytic network process: An overview of applications," *Applied Mathematics and Computation*, vol. 367, Feb. 2020, Art. no. 124780. doi: https://doi.org/10.1016/j.amc.2019.124780.
[27] I. Etikan, "Comparison of convenience sampling and purposive sampling," *American Journal of Theoretical and Applied Statistics*, vol. 5, no. 1, pp. 1-4, 2016. doi: https://doi.org/10.11648/j.ajtas.20160501.11.