International Journal of Marine Engineering Innovation and Research, Vol. 11(3), Sept. 2026. 859-868
(pISSN: 2541-5972, eISSN: 2548-1479)

Fire Mitigation-Based Cargo Stowage of Solid-State Battery Electric Vehicles on ASDP Ferry Decks: A Mixed-Method Risk Assessment Study on the Padang–Mentawai Route

Rizal Rochmansyah[1*], Marudut Bernadtua Simanjutak[2], Bayu Yudho Baskoro[3], Achmad Ali Mashartanto[4], Muhammad Fachruddin Raihan[5].

(Received: 8 June 2026 / Revised: 12 June 2026 / Accepted: 24 June 2026 / Available Online: 1 September 2026)

***Abstract*—** The rapid proliferation of solid-state battery electric vehicles (EVs) in Indonesia has introduced an unprecedented fire safety challenge for domestic ferry operations, particularly on high-risk routes such as Padang–Mentawai where extreme maritime environmental conditions compound battery degradation risks. This study examines the influence of EV cargo stowage practices and human resource capacity for fire mitigation on maritime safety perception aboard ASDP ferries. Employing a mixed-method design integrating quantitative Likert-scale surveys ($N = 60$; $\alpha = 0.892$), semi-structured qualitative interviews, and Focus Group Discussions (FGD), data were collected from maritime students, lecturers, and seafarers affiliated with Politeknik Pelayaran Sumatera Barat between February and June 2026. Multiple regression analysis revealed a significant combined effect of cargo stowage (X2) and fire mitigation capacity (X3) on maritime safety perception (Y), with $r = 0.712$ ($p < 0.01$). Risk matrix analysis identified 65% of 18 risk indicators at high or extreme levels, concentrated in maritime environmental conditions and emergency response readiness. FGD findings revealed three structural gaps between SE-DJPL No. 12/2024 and operational practice: insufficient deck infrastructure, seafarer competency deficits in thermal runaway management, and coordination failures among operators, regulators, and port charging providers. The study contributes a risk-based adaptive SOP model for EV cargo stowage and recommends curriculum integration at maritime polytechnic institutions.

Keywords— *electric vehicle; solid-state battery; cargo stowage; fire mitigation; ASDP ferry; maritime safety; thermal runaway*

Corresponding Author: rizal.rochmansyah@gmail.com

I. INTRODUCTION

The global energy transition has arrived at the waterline. As decarbonization imperatives drive the rapid electrification of land-based transport, the maritime sector faces a compound challenge that extends well beyond its own propulsion systems: the growing volume of battery-powered vehicles transported aboard roll-on/roll-off (ro-ro) ferries now introduces fire hazards of a fundamentally different character than those for which existing vessel safety architectures were designed [1]. In Indonesia, this convergence of energy policy and maritime operations has emerged as a critical and underexamined safety frontier. Presidential Regulation No. 79/2023 has accelerated the national adoption of electric vehicles (EVs), projecting a national fleet of over two million EVs by the late 2020s, and with Indonesia's archipelagic geography placing ferry transportation at the heart of inter-island mobility, the intersection between EV proliferation and passenger ferry safety is no longer a theoretical concern — it is an operational reality with immediate consequences for human life, regulatory architecture, and institutional preparedness [2]. The challenge is not hypothetical: global incident records from 2022 to 2024, including high-profile vessel fires involving EV cargo on European and East Asian routes, have demonstrated that thermal runaway events aboard ro-ro vessels can result in total loss of vessel and cargo, mass evacuation events, and fatalities [21].

The emergence of solid-state battery technology deepens the complexity of this challenge considerably. Unlike conventional lithium-ion batteries, solid-state variants utilize non-flammable solid electrolytes that theoretically reduce thermal runaway probability below 1% under standard conditions [3]. However, the high energy density of these batteries — exceeding 450 Wh/kg compared to 250–300 Wh/kg for lithium-ion — means that when thermal runaway does occur, the thermal release is substantially more intense and harder to arrest [4]. The maritime transport context introduces further variables: mechanical vibration during loading and unloading, humidity exposure in tropical climates, elevated ambient temperatures, and the confined geometry of ro-ro decks that concentrate any fire event within a poorly ventilated space [5]. On the Padang–Mentawai route specifically, wave heights regularly reaching 4–6 metres create dynamic loading conditions on battery cells that laboratory-based risk assessments do

Rizal Rochmansyah, Politeknik Pelayaran Sumatera Barat, West Sumatera, Indonesia, Email: rizal.rochmansyah@gmail.com
Marudut Bernadtua Simanjutak, Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia, Email: bernadmarudut@gmail.com
Bayu Yudho Baskoro, Politeknik Pelayaran Sumatera Barat, West Sumatera, Indonesia, Email: bayuyudho60@gmail.com
Achmad Ali Mashartanto, Politeknik Pelayaran Sumatera Barat, West Sumatera, Indonesia, Email: alimashartanto@gmail.com
Muhammad Fachruddin Raihan. Politeknik Pelayaran Sumatera Barat, West Sumatera, Indonesia, Email: Muhammad.Fachruddin.Raihan@poltekpelsumbar.ac.id

not fully capture. These compounding contextual stressors are absent from the European and East Asian ferry contexts in which most existing EV maritime fire research has been conducted, creating a significant empirical gap in the global knowledge base on this hazard.

Despite these compounding risks, the regulatory and operational infrastructure governing EV transport on Indonesian domestic ferries remains nascent and, in critical respects, inadequate. SE-DRJD No. 7/2024 — issued specifically for the 2024 Lebaran transport period by the Directorate General of Land Transportation — provided a first procedural framework for EV loading zones, manifest recording, and crew patrol obligations [6]. The more durable SE-DJPL No. 12/2024, issued by the Directorate General of Sea Transportation, extended these provisions into a standing operational guideline for sea-going vessels under Indonesian flag carrying electric vehicles [7]. Yet the issuance of regulation and the internalization of its requirements by ship operators, port authorities, and crew members are substantially different phenomena. International evidence from analogous regulatory transitions — including the ISM Code's documented implementation gaps between formal compliance and operational effectiveness [8] — consistently demonstrates that regulatory frameworks alone do not produce the behavioral and infrastructural changes required for genuine safety improvement. Rudijanto [22] identified specific regulatory gaps in Indonesia's EV battery fire governance that remain unresolved in the 2024 regulatory instruments, particularly around the management of state of charge at port interfaces and the absence of vessel-specific risk assessment requirements for routes with distinctive environmental profiles.

The fire risk profile of EVs in maritime settings has attracted increasing scholarly attention in recent years. Lee et al. [1] demonstrated through controlled experiments that the state of charge (SoC) at the time of ignition significantly influences fire dynamics and suppression efficacy, with high-SoC batteries producing heat release rates that conventional CO_2 and foam suppression systems cannot contain. Ayci, Barlas, and Olcer [5] employed fire dynamics simulation to evaluate the performance of current ferry deck layouts under EV fire scenarios, finding that standard ventilation configurations accelerate flame spread rather than retarding it. Waskito et al. [9] applied system-theoretic process analysis and Bayesian Network modeling to EV transport via Indonesian waterways, identifying a cluster of unsafe control actions in the loading interface between port operators and vessel crew that current SOPs do not address. Pitana et al. [21] similarly found through simulation that EV fires on ro-ro ferries spread laterally between vehicles with a speed and intensity that substantially exceeds the response capacity of standard vessel fire management procedures. Collectively, these studies establish that the fire hazard posed by EVs in ro-ro maritime contexts is technically distinctive, operationally underaddressed, and contextually intensified in the Indonesian archipelagic setting. However, none has examined the specific intersection of solid-state battery technology, mixed fleet composition, institutional preparedness of maritime education actors, and the Padang–Mentawai operational environment — the precise configuration that the present study addresses.

This knowledge gap is not merely academic. The Padang–Mentawai route carries a mixed cargo of conventional and electric vehicles across one of Indonesia's most climatically demanding sea passages, linking West Sumatra's provincial capital to a remote island group with limited emergency response infrastructure and no realistic prospect of external fire service assistance during an onboard incident. A fire event aboard an ASDP vessel on this route would be remote from port-based fire services, occurring in conditions of high humidity and significant vessel motion, with limited crew capacity for specialized battery suppression. Fu et al. [10] have argued that fire risk on passenger vessels demands integrated assessment frameworks that account for both technical ignition pathways and organizational response capacities — precisely the dimensions that remain empirically unmeasured on this route. The urgency of this gap is compounded by ASDP's own coordination with Kemenhub, which as of June 2026 acknowledged that implementation of standing EV ferry guidelines remains suboptimal across the domestic network [7].

The present study was therefore designed to address three interrelated research objectives. First, to analyze the current practices of EV cargo stowage and the understanding of vessel crew regarding EV fire risk characteristics aboard ASDP ferries on the Padang–Mentawai route. Second, to identify the operational constraints and regulatory gaps in implementing fire mitigation-based EV stowage on domestic ro-ro ferries. Third, to formulate a risk-based safety improvement strategy grounded in ISO 31000:2018, informed by empirical data from three distinct stakeholder groups: maritime students, academic instructors, and active seafarers affiliated with Politeknik Pelayaran Sumatera Barat.

The significance of this inquiry operates at multiple levels. Theoretically, it extends the emerging literature on EV maritime fire risk into the domain of solid-state battery technology and the tropical-maritime context — a domain in which published empirical evidence remains sparse and simulation-based methodologies predominate. Empirically, it generates the first systematic mixed-method assessment of EV stowage and fire mitigation practices on this specific route, drawing on the perspectives of actors who are directly implicated in operationalizing safety standards. Practically, the findings inform an adaptive SOP framework and contribute to the curriculum development agenda of Indonesia's maritime polytechnic institutions, which are tasked with preparing the next generation of seafarers for a decarbonizing, electrifying fleet [11]. In this respect, the study engages Dewan and Godina's [12] critical observation that seafarers remain both the most critical and the most underequipped actors in maritime energy transition — an observation whose implications are acute when the transition in question involves transporting batteries capable of igniting catastrophic, self-sustaining fires in confined spaces at sea, far from shore-based assistance. Simanjuntak et al. [23] have further argued, from the Indonesian maritime education context, that institutional capacity building in maritime polytechnics must remain responsive to the operational realities confronting their graduates — a principle that the present study operationalizes through its empirical focus on the competency gap between regulatory expectation and seafarer preparedness.

The paper proceeds as follows. Section 2 reviews the theoretical and empirical literature underpinning the study's conceptual framework, synthesizing four bodies of scholarship — EV battery fire dynamics, cargo stowage theory, maritime safety management, and seafarer competency development — into a coherent conceptual position that justifies the study's integrative analytical design. Section 3 describes the mixed-method research design and analytical procedures, detailing the sampling rationale, instrument development, and the three-tier analytical strategy combining quantitative regression, ISO 31000 risk matrix construction, and thematic analysis of qualitative data. Section 4 presents the quantitative and qualitative findings with integrated interpretation, organized around the study's three research objectives. Section 5 discusses the significance, theoretical contributions, practical implications, and limitations of the results, situating the findings in relation to the international literature on EV maritime fire safety. Section 6 concludes with a synthesis of contributions and directions for future research, with particular emphasis on the replication agenda across Indonesia's broader domestic ferry network. Section 2 reviews the theoretical and empirical literature underpinning the study's conceptual framework. Section 3 describes the mixed-method research design and analytical procedures. Section 4 presents the quantitative and qualitative findings with integrated interpretation. Section 5 discusses the significance, implications, and limitations of the results. Section 6 concludes with a synthesis of contributions and directions for future research.

II. LITERATURE REVIEW

2.1 Electric Vehicle Battery Technology and Thermal Runaway Dynamics

Understanding the fire hazard associated with EVs in maritime settings requires, as a conceptual point of departure, a technically informed account of battery behavior under stress conditions. The dominant battery chemistry in contemporary EVs — lithium-ion — stores energy through the reversible intercalation of lithium ions between electrodes. The very property that makes this chemistry attractive for transport applications, namely high energy density, is also the source of its primary safety liability: when the electrochemical equilibrium of a lithium-ion cell is disrupted by mechanical damage, overcharging, or thermal stress, the system enters a self-reinforcing exothermic cascade known as thermal runaway [1]. The heat generated by one stage of degradation accelerates the next, producing temperatures that can exceed 800°C and releasing hydrogen fluoride, carbon monoxide, and other toxic combustion gases that render conventional firefighting procedures both ineffective and hazardous to personnel [4].

Solid-state battery technology, which replaces the liquid electrolyte with a ceramic or polymer solid medium, substantially alters this risk profile. The elimination of flammable liquid electrolyte reduces the probability of thermal runaway under normal operating conditions to below 1% — a significant theoretical improvement over lithium-ion's 5–10% incidence under comparable stress scenarios [3]. However, the higher energy density of solid-state cells means that any thermal runaway event releases heat at a greater rate and magnitude than equivalent lithium-ion failures. Moreover, solid-state batteries are in the early stages of mass commercialization as of 2025–2026, meaning that empirical data on their behavior under maritime-specific stressors — vibration, humidity, salt air, thermal cycling — remain limited. This data gap constitutes a significant challenge for risk assessment frameworks that rely on actuarial evidence accumulated from historical incident data [9].

Lee et al. [1] conducted controlled burn experiments on EV batteries at varying states of charge, finding that higher SoC values at the time of thermal runaway initiation produced substantially greater peak heat release rates and longer sustained combustion. This finding has direct operational implications: an EV with a fully charged battery, such as one that has used a fast-charging station near the port before boarding, presents a materially higher fire risk profile than one with a partially depleted battery. The study also found that water cooling — the application of continuous large-volume water streams — was the only suppression technique capable of preventing re-ignition, and that premature cessation of cooling consistently resulted in secondary thermal runaway events. These findings challenge the adequacy of the current suppression infrastructure aboard most domestic Indonesian ferries, which is designed around Class A and Class B fires rather than the sustained thermal management requirements of lithium-ion or solid-state battery combustion.

2.2 Cargo Stowage Theory and EV-Specific Adaptation

Stowage theory in maritime operations encompasses the systematic arrangement of cargo aboard a vessel to optimize stability, safety, accessibility, and operational efficiency [13]. On ro-ro vessels, where vehicle cargo is self-propelled aboard rather than craned, stowage planning involves not only weight distribution across the vessel's metacentric height but also the management of spatial relationships between vehicle categories. Pérez-Canosa and Orosa [13] demonstrated that non-standardized cargo — cargo with physical or risk characteristics that fall outside standard loading frameworks — requires specialized securing methodologies that account for the dynamic forces encountered during transit, including wave-induced vessel motion and vibration.

EVs constitute precisely this category of non-standardized cargo in the maritime context. Their distinctive risk profile — principally the battery fire hazard discussed above — requires that stowage planning integrate fire mitigation considerations that are absent from conventional vehicle loading procedures. SE-DJPL No. 12/2024 operationalizes this requirement through a set of spatial prescriptions: EV designation zones with adequate ventilation, minimum separation distances from machinery spaces (at minimum 3 metres unless A-60 insulation is present), and mandatory manifest recording to ensure that port and vessel authorities are aware of the EV proportion of each cargo manifest [7]. However, as Waskito et al. [9] observed in their analysis of EV transport risk on Indonesian waterways, the procedural intent of these regulations encounters structural obstacles at the operational interface — specifically, the absence of designated EV zones on many existing ASDP vessels, insufficient ventilation capacity for high-density EV loading, and the absence of thermal monitoring technology capable of detecting pre-thermal runaway temperature elevations in battery cells during transit.

Ayci et al. [5] used fire dynamics simulation to model EV fire spread on ro-ro ferries under varying stowage configurations, finding that the proximity of EVs to one another was among the most significant predictors of fire spread rate. Their simulations suggested that a minimum spacing of 2–3 metres between EVs substantially reduced fire propagation risk, but noted that current loading densities on commercial ferry routes — including high-traffic domestic Indonesian routes — make this spacing impractical without dedicated EV zones equipped with fire suppression and ventilation infrastructure. Peša et al. [14] examined ferry electrification more broadly and highlighted that the charging infrastructure at ports significantly influences onboard battery SoC at departure — a variable that, as Lee et al. [1] demonstrated, directly affects fire risk magnitude. The absence of controlled charging management at Indonesian domestic ferry ports thus constitutes an upstream risk factor that stowage procedures alone cannot neutralize.

2.3 Maritime Safety Management and Risk Assessment Frameworks

Maritime safety management has been institutionalized at the international level through the ISM Code, which requires shipping companies to develop and implement Safety Management Systems (SMS) addressing all identified hazards in their operational profile [8]. The ISM Code's effectiveness, however, is contingent on the translation of formal documentation into genuine operational practice — a translation that Mok et al. [8] examined through longitudinal analysis of maritime accident data, finding that ISM Code compliance did not consistently produce reductions in accident frequency unless accompanied by genuine organizational safety culture change. This finding resonates with Bokau et al.'s [15] study of maritime safety in Makassar Port, Indonesia, which employed Functional Resonance Analysis Method (FRAM) to demonstrate that safety outcomes on Indonesian domestic ferry routes are shaped as much by informal operational practices and inter-agency coordination patterns as by formal regulatory compliance.

ISO 31000:2018 provides a complementary risk management framework that is gaining traction in maritime contexts for its systematic approach to risk identification, analysis, evaluation, and treatment [16]. Unlike the ISM Code's primarily compliance-oriented structure, ISO 31000 is explicitly process-oriented, providing methodological guidance for constructing risk matrices that integrate likelihood and severity dimensions across technical, operational, human, and environmental risk categories. Fu et al. [10] applied an integrated risk assessment framework combining FMEA, risk matrix analysis, and hybrid causal logic modeling to passenger ship fire accidents, demonstrating that multi-dimensional analytical approaches capture accident pathways that single-method assessments miss. The application of ISO 31000 to EV cargo stowage on domestic Indonesian ferries — as employed in the present study — thus extends the methodological frontier of maritime fire risk assessment into a context where formal risk documentation is absent and operational data on EV incidents remains limited.

2.4 Human Resource Capacity and Seafarer Competency

The human dimension of maritime safety management is consistently identified in the literature as the most consequential variable in accident causation and prevention [11]. Shi et al. [11] demonstrated through Bayesian network modeling that despite extensive STCW framework provisions for seafarer competency, human error attributable to inadequate situational understanding and skill deficits remains a leading contributor to maritime accidents in restricted waters. Dewan and Godina [12] examined the specific challenge of energy efficiency operational measures — a domain analogous in many respects to EV fire management — and found that seafarers' implementation of new technical procedures was systematically undermined by gaps in conceptual understanding, insufficient practical training, and the absence of institutional support structures for embedding new knowledge in routine operations.

In the context of EV cargo handling, this competency challenge assumes particular acuity. Thermal runaway management, battery SoC inspection, and specialized suppression techniques are all knowledge domains that fall outside the conventional firefighting and safety training curricula of maritime education institutions [5]. The present study's inclusion of maritime students, lecturers, and active seafarers as research participants reflects a deliberate attempt to triangulate the competency gap across its institutional, pedagogical, and operational dimensions — a methodological choice informed by Zhao et al.'s [17] mixed-method approach to barrier analysis in maritime industry capability development, which demonstrated that cross-stakeholder comparison reveals competency and systemic gaps that single-group analysis conceals.

2.5 Research Gap and Conceptual Position

Synthesizing the literature across these four domains, several critical gaps are evident. Empirically, no published study has examined EV cargo stowage practices and fire mitigation capacity specifically in the context of solid-state battery technology on Indonesian domestic ferry routes. Contextually, the Padang–Mentawai operational environment — characterized by extreme wave conditions, tropical humidity, remote route geography, and limited port emergency infrastructure — introduces risk amplifiers that are absent from studies conducted in European or East Asian ferry contexts [5], [9]. Methodologically, the existing literature on EV maritime fire risk is dominated by simulation-based and technical studies; mixed-method approaches that integrate quantitative risk assessment with qualitative stakeholder perspectives remain rare [17]. Institutionally, the role of maritime education institutions in bridging the competency gap between regulatory requirements for EV safety management and operational seafarer knowledge has not been systematically examined.

The present study is positioned at the intersection of these gaps. Its conceptual framework integrates stowage theory, ISO 31000 risk assessment, ISM Code compliance analysis, and human resource capacity evaluation to produce a holistic account of EV fire safety management on a specific, high-risk domestic ferry route. This integrative positioning enables the study to address not merely technical hazard parameters but the full socio-technical system — regulatory, operational, institutional, and environmental — within which EV cargo stowage decisions are made and fire risks are either effectively managed or allowed to escalate.

III. METHOD

This study employed a concurrent mixed-method design, integrating quantitative survey data, qualitative interview findings, and Focus Group Discussion (FGD) results to produce a triangulated account of EV cargo stowage practices and fire mitigation capacity on the Padang–Mentawai ASDP ferry route. Data collection was conducted between February and June 2026 at Politeknik Pelayaran Sumatera Barat and Pelabuhan Bungus, Padang [18].

The study population comprised three stakeholder groups directly implicated in EV maritime safety: maritime students, lecturers and instructors, and active seafarers — including deck officers and ratings — affiliated with Politeknik Pelayaran Sumatera Barat and with operational experience on the Padang–Mentawai route. A purposive sampling approach was employed, selecting participants on the basis of direct relevance to the research objectives: specifically, experience with EV cargo handling, maritime safety management, or maritime education pertaining to fire safety and cargo operations. A total of N = 60 valid respondents were recruited, distributed across the three stakeholder groups to ensure cross-stakeholder comparability [19]. For the qualitative components, 8–12 participants with the deepest operational experience were selected for in-depth interviews and FGD participation, using snowball sampling to identify additional informants until theoretical saturation was reached.

The primary quantitative instrument was a five-point Likert-scale questionnaire comprising 32 valid items following instrument testing, organized around five variable clusters: EV knowledge and awareness (X1), cargo stowage practices (X2), fire mitigation human resource capacity (X3), regulatory compliance (X4), and maritime safety perception (Y). Instrument reliability was confirmed at $\alpha = 0.892$, exceeding the 0.70 threshold.

TABLE 1.
DESCRIPTIVE STATISTICS BY VARIABLE CLUSTER (N = 60)

Variable	Mean	SD	Category
X1 — EV Knowledge & Awareness	3.72	0.61	Good
X2 — Cargo Stowage Practices	3.18	0.74	Moderate
X3 — Fire Mitigation HR Capacity	2.89	0.82	Moderate–Poor
X4 — Regulatory Compliance	3.45	0.69	Good
Y — Maritime Safety Perception	3.61	0.71	Good

Mean scores indicate that respondents hold relatively positive perceptions of maritime safety (Y = 3.61) and regulatory compliance (X4 = 3.45), yet report considerably weaker actual practice in cargo stowage (X2 = 3.18) and, most critically, in fire mitigation human resource capacity (X3 = 2.89). This divergence between regulatory awareness and operational capability is a structurally significant finding: high X4 scores do not translate automatically into high X2 or X3 performance, suggesting that regulatory knowledge and operational preparedness are decoupled in this context. This decoupling echoes Mok et al.'s [8] finding that ISM Code awareness does not guarantee effective safety management behavior, and Bokau et al.'s [15] observation that formal compliance metrics systematically overstate actual safety performance on Indonesian domestic ferry routes.

The 78% of respondents who demonstrated adequate understanding of solid-state battery risk characteristics — one of the study's headline quantitative findings — must be interpreted against this backdrop. While the majority of respondents are cognitively aware of the distinctive fire hazard posed by solid-state EV batteries, the gap between this awareness and operational capacity (reflected in the X3 mean of 2.89) represents the central competency problem the study identifies.

4.2 Multiple Regression Analysis: Stowage and Mitigation Capacity as Predictors of Safety Perception

Multiple regression analysis was conducted to examine the combined predictive effect of cargo stowage practices (X2) and fire mitigation human resource capacity (X3) on maritime safety perception (Y). The results are presented in Table 2.

TABLE 2.
MULTIPLE REGRESSION RESULTS: X2 AND X3 PREDICTING MARITIME SAFETY PERCEPTION (Y)

Predictor	B	Std. Error	β	t	p
Constant	1.24	0.31	—	4.00	< .001
X2 — Cargo Stowage Practices	0.41	0.09	0.38	4.56	< .001
X3 — Fire Mitigation HR Capacity	0.47	0.10	0.43	4.70	< .001

Note: $R = 0.712$, $R^2 = 0.507$, $F(2,57) = 29.27$, $p < .001$

The model explains 50.7% of the variance in maritime safety perception ($R^2 = 0.507$), with both predictors making statistically significant independent contributions. Notably, X3 (β = 0.43) exerts a slightly stronger standardized influence on Y than X2 (β = 0.38), indicating that respondents' safety perceptions are more strongly shaped by their assessment of crew fire management competency than by stowage practice quality alone. This finding is theoretically consistent with Shi et al.'s [11] demonstration that human competency variables are stronger predictors of maritime safety outcomes than procedural compliance variables — and has direct implications for the allocation of institutional investment between infrastructure improvement and training program development.

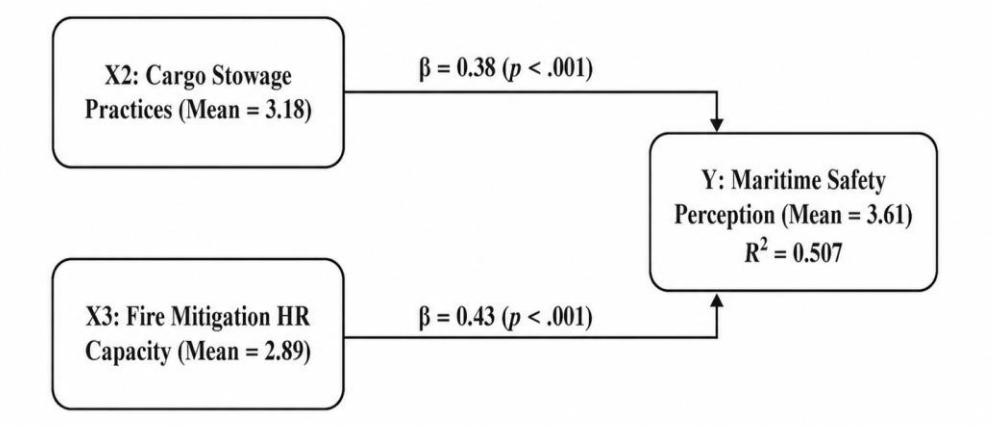

Figure 1. Regression Path Model: Influence of X2 and X3 on Maritime Safety Perception (Y)

4.3 ISO 31000 Risk Matrix Analysis

The 18-indicator risk matrix, developed through the ISO 31000:2018 protocol across four dimension categories, produced the distribution presented in Figure 2. Across all 18 indicators, 65% were classified at the high or extreme risk level, with the highest concentrations in the environmental and human resource dimensions.

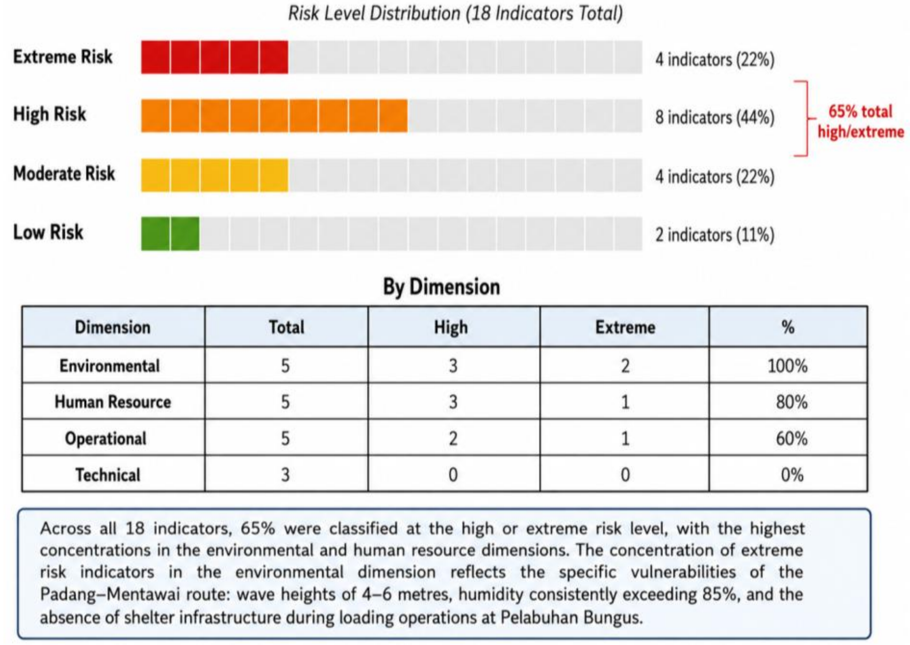

Figure 2. Distribution of Risk Indicators by Category and Risk Level

The concentration of extreme risk indicators in the environmental dimension reflects the specific vulnerabilities of the Padang–Mentawai route: wave heights of 4–6 metres, humidity consistently exceeding 85%, and the absence of shelter infrastructure during loading operations at Pelabuhan Bungus. Waskito et al. [9] identified comparable environmental loading conditions as significant risk amplifiers for EV battery transport in Indonesian waters, and the present findings confirm this assessment through direct stakeholder data. The high-risk classification of 80% of human resource indicators — covering crew training adequacy, drill frequency, suppression technique knowledge, and emergency coordination protocols — is consistent with Dewan and Godina's [12] finding that seafarers implementing novel energy-related procedures face structural knowledge gaps that standard maritime training curricula do not address.

Critically, the zero extreme-risk rating in the technical dimension — covering the EV battery systems themselves — should not be interpreted as indicating low technical risk. Rather, it reflects respondents' relatively high awareness (78%) of EV battery risk characteristics, which positions the technical knowledge dimension at the high rather than extreme end. The risk is not ignorance of what solid-state batteries can do; it is the operational incapacity to prevent and respond to the events that respondents know are possible.

This interpretation is further supported by cross-tabulation of variable scores by respondent group. Seafarers returned the lowest mean scores on X3 ($M = 2.61$, $SD = 0.79$) of the three groups, indicating that the competency deficit is most acute precisely among the actors with direct operational responsibility for fire management aboard vessel decks. Lecturers returned the highest X4 scores ($M = 3.78$), reflecting their regulatory knowledge depth, while students occupied the intermediate range across all variables (X3: $M = 2.97$), consistent with their stage of professional preparation. This cross-group pattern aligns with Zhao et al.'s [17] finding that mixed-method cross-stakeholder analysis systematically reveals competency gradient structures that single-group studies obscure. It also provides a sharper empirical target for curriculum intervention: the competency gap is most acute, and the safety stakes are highest, in the active seafarer group — not the student population that maritime education programs most directly reach, suggesting that continuing professional development programs rather than initial education modules should be the primary institutional response.

4.4 Qualitative and FGD Findings: Three Structural Gap Themes

Thematic analysis of interview transcripts and FGD records identified three principal structural gap themes that recur across all stakeholder groups, with varying emphases by group. These themes explain the mechanism through which regulatory awareness fails to translate into operational safety competence.

Theme 1: Insufficient Deck Infrastructure and Thermal Monitoring

All three stakeholder groups independently identified the absence of designated EV zones with adequate ventilation as the most tangible operational gap. Seafarers reported that on current ASDP vessels, EVs are positioned wherever space permits during the loading process, with no systematic enforcement of the designated zone requirement specified in SE-DJPL No. 12/2024 [7]. Lecturers noted that ventilation ratings on ASDP vessels of the generation currently operating on the Padang–Mentawai route fall below the standards recommended by Ayci et al. [5] for EV fire incident management. Students, drawing on their practical training exposure, observed that no vessel they had encountered during practical placements was equipped with thermal imaging or IoT-based temperature monitoring on the vehicle deck — a technology that Fu et al. [10] identify as essential for the early detection of pre-thermal runaway cell temperature elevation.

Theme 2: Seafarer Competency Deficits in Thermal Runaway Management

Across the three FGD sessions, participants consistently identified the competency gap in thermal runaway-specific fire management as more serious than the infrastructure gap. Seafarers reported having received no training specific to EV or solid-state battery fires, and described uncertainty about the correct suppression procedures — specifically, whether to use CO_2, dry powder, or sustained water cooling, and when re-ignition monitoring should conclude. This uncertainty is operationally hazardous: as Lee et al. [1] demonstrated, premature cessation of water cooling is the most consistent precipitant of secondary thermal runaway. Lecturers acknowledged that current maritime education curricula at Politeknik Pelayaran Sumatera Barat do not include EV fire management as a dedicated module, reflecting a broader gap in Indonesian maritime education that leaves seafarers underprepared for the cargo environments they now routinely encounter.

Theme 3: Coordination Failures Among Operators, Regulators, and Charging Providers

The third structural gap theme concerns the systemic coordination architecture governing EV loading decisions. FGD participants identified three distinct coordination failures: between ASDP vessel operators and port charging facility providers regarding departure SoC levels; between ASDP operational management and KSOP inspectors regarding EV manifest recording compliance; and between Kemenhub as the regulatory authority and ASDP as the operational entity regarding the practical application of SE-DJPL No. 12/2024 provisions to vessel-specific conditions. Bokau et al.'s [15] FRAM analysis of Indonesian port safety identified analogous coordination gaps as primary contributors to safety performance variability — findings that the present study extends from port operations to the specific domain of EV cargo management.

V. DISCUSSION

5.1 Answering the Research Objectives

The study's findings provide convergent empirical answers to all three research objectives. With respect to the first objective — analyzing current EV stowage practices and crew understanding — the data reveal a structurally significant divergence between cognitive awareness of EV fire risk and operational capacity to manage it. The 78% adequate-understanding rate among respondents is, on its face, an encouraging indicator of the regulatory communication effort that followed SE-DJPL No. 12/2024. But the X3 mean of 2.89 and the 80% high-risk classification of human resource indicators disclose that awareness has not been translated into the procedural competency, training consolidation, or drill practice that effective emergency response requires. This pattern is consistent with Dewan and Godina's [12] framework, which distinguishes between conceptual knowledge of energy-related risks and the operational embedding of response procedures — and identifies the latter as systematically underdeveloped across the maritime sector during periods of technological transition. The implication is that the current regulatory communication strategy, while successful in building awareness, is insufficient as a safety intervention; it must be supplemented by structured competency development programs embedded in institutional maritime education curricula.

With respect to the second objective — identifying operational constraints and regulatory gaps — the three FGD-derived structural gap themes provide a granular account of the mechanisms through which SE-DJPL No. 12/2024 fails to achieve its safety objectives in practice. The infrastructure gap reflects the vessel generation mismatch: regulations written for vessels with designated EV zones and thermal monitoring capability are applied to vessels not designed for this purpose. This is not a compliance failure in the conventional sense — it is a capital infrastructure constraint that regulatory prescription alone cannot resolve. Ayci et al. [5] identified the same structural tension in their simulation study of ferry decks, finding that fire safety regulation routinely outpaces vessel infrastructure investment. The competency gap reflects institutional lag between regulatory specification and curriculum adaptation at maritime polytechnics. The coordination failure engages the regulatory architecture identified by Mok et al. [8] as the persistent weakness of maritime safety management: the translation gap between institutional mandate and operational practice that Bokau et al. [15] documented for Indonesian domestic ferry routes more broadly.

With respect to the third objective — formulating a risk-based safety improvement strategy — the integrated findings from the ISO 31000 risk matrix, the regression model, and the qualitative themes converge on a coherent strategic direction: the highest-return safety investments are in human resource capacity development and upstream SoC regulation at port charging facilities, both of which address the risk indicators with the highest severity-likelihood combinations and the strongest predictive relationship with safety perception outcomes. This convergence across three independent data sources — quantitative regression, risk matrix construction, and FGD consensus — constitutes the methodological triangulation that validates the study's principal recommendations, reducing the likelihood that the identified priorities reflect the biases of any single method or stakeholder group [20]. The three structural gap themes (deck infrastructure, seafarer competency, inter-agency coordination) are not competing explanations but complementary dimensions of a single systemic failure: the absence of an integrated, route-specific EV safety management system that connects regulatory requirements to operational procedures, vessel infrastructure standards, and seafarer training programs.

5.2 Theoretical Contributions

The study's most significant theoretical contribution is its empirical demonstration that the introduction of solid-state battery EVs into a domestic ferry route creates a composite risk profile that no single analytical framework adequately characterizes. The technical fire risk, the operational stowage infrastructure risk, the human resource competency risk, and the environmental risk of the Padang–Mentawai route conditions interact in ways that the ISO 31000 mixed-method matrix captures more completely than either fire dynamics simulation [5] or system-theoretic process analysis [9] alone. The cross-stakeholder mixed-method design, drawing on Zhao et al.'s [17] approach, surfaces institutional and organizational risk dimensions that technical modeling cannot access.

The regression finding that X3 ($\beta = 0.43$) exerts a stronger influence on maritime safety perception than X2 ($\beta = 0.38$) carries a specific theoretical implication: in novel cargo hazard contexts, stakeholders' aggregate safety assessment is more sensitive to confidence in human emergency response capacity than to physical infrastructure adequacy. This is consistent with Bokau et al.'s [15] finding that Indonesian maritime safety actors privilege organizational competency factors in safety judgments, and with Fu et al.'s [10] integrated passenger vessel fire risk framework, which identifies emergency response organizational capacity as a stronger predictor of casualty outcomes than the technical fire characteristics themselves. The contextual finding that the technical risk dimension receives zero extreme classifications — despite solid-state batteries being the highest energy-density commercial battery type — reveals a shift in the governance frontier: from awareness deficit to response incapacity. This is qualitatively distinct from the knowledge-gap problems that earlier EV fire risk studies addressed and demands a qualitatively different policy response focused on competency embedding rather than information dissemination.

5.3 Practical and Policy Implications

The study's practical implications operate at three institutional levels. At the vessel operations level, the findings support the development of an adaptive SOP integrating SoC inspection and threshold enforcement at the loading interface, designated zone protocols tailored to existing vessel geometries, and thermal runaway response procedures specifying sustained water cooling duration and re-ignition monitoring consistent with Lee et al.'s [1] experimental parameters — specifically, continuous cooling for a minimum of four hours post-suppression and thermal monitoring for 24 hours thereafter. At the regulatory level, the findings support expanding SE-DJPL No. 12/2024 to include port charging SoC management requirements, inter-agency coordination protocols between KSOP and ASDP operations, and vessel upgrade timelines tied to EV traffic volume thresholds on each route. At the maritime education level, the findings provide empirical grounding for introducing a dedicated EV maritime safety module at Politeknik Pelayaran Sumatera Barat, covering solid-state battery characteristics, thermal runaway management, specialized suppression, and EV manifest procedures — aligned with the STCW-framework responsiveness imperative identified by Shi et al. [11] and the institutional capacity building agenda of Simanjuntak et al. [23].

5.3 Practical and Policy Implications

The study's practical implications operate across three institutional levels, each demanding a different type of response. At the vessel operations level, the findings support the immediate development of an adaptive SOP for EV cargo stowage that integrates SoC inspection and threshold enforcement at the loading interface — specifically, a maximum departure SoC ceiling for EVs permitted to board, enforced through the manifest recording mechanism already specified in SE-DJPL No. 12/2024. This SoC threshold should be calibrated to the route's emergency response capacity: on the Padang–Mentawai route, where suppression resources are limited and transit times can be extended by adverse weather, a more conservative SoC ceiling than on well-equipped short-haul routes is empirically justifiable. The SOP should also specify sustained water-cooling duration parameters and re-ignition monitoring protocols consistent with Lee et al.'s [1] experimental findings — specifically, continuous cooling for a minimum of four hours post-suppression and thermal monitoring for 24 hours thereafter — parameters that are absent from current ASDP operational guidelines.

At the regulatory level, the three structural gap themes collectively support an expansion of SE-DJPL No. 12/2024 provisions in three directions. First, port charging facility SoC management requirements should be incorporated, creating a regulatory obligation for port operators to enforce departure SoC limits analogous to the dangerous goods quantity limits already embedded in IMDG Code provisions [24]. Second, inter-agency coordination protocols between KSOP inspectors and ASDP operations management should be formalized, specifying responsibility allocation for EV manifest verification, zone compliance inspection, and post-departure thermal monitoring reporting. Third, vessel infrastructure upgrade timelines should be established, with minimum ventilation standards, designated EV zone dimensions, and thermal monitoring technology requirements tied to EV traffic volume thresholds on each route. This staged infrastructure approach reflects the capital constraint reality identified in the FGD findings while establishing clear regulatory endpoints that ASDP can plan toward.

At the maritime education level, the cross-group competency gradient finding — seafarers (X3 = 2.61) more severely underequipped than students (X3 = 2.97) — has a counterintuitive institutional implication: continuing professional development programs targeting active seafarers must be prioritized over initial curriculum additions to student programs. The former addresses the acute operational safety gap; the latter addresses the long-term pipeline. Both are necessary, but the sequencing matters given resource constraints. Politeknik Pelayaran Sumatera Barat is positioned to lead both initiatives through its network relationships with ASDP operators and its access to active seafarers through refresher training programs, representing a concrete institutional pathway for translating the study's empirical findings into improved operational safety outcomes [23].

5.4 Limitations and Future Research

The study's primary limitation is the single-route, single-institution sampling frame. The Padang–Mentawai route was selected for its operational criticality, environmental distinctiveness, and the institutional accessibility of Politeknik Pelayaran Sumatera Barat's stakeholder networks — but these same selection criteria limit the external validity of the findings. Ferry routes with different vessel generations, traffic compositions, port infrastructure, and environmental conditions will present different risk profiles, and the regression coefficients and risk indicator distributions reported here should be treated as route-specific findings rather than generalizable parameters. Future research should replicate the mixed-method risk assessment protocol on high-traffic routes — particularly Merak–Bakauheni and Ketapang–Gilimanuk — where EV volumes are substantially higher and where the infrastructure and institutional context differs significantly from the Padang–Mentawai case.

The cross-sectional design precludes causal inference about the relationship between SOP implementation and safety outcomes. The regression model establishes predictive associations, not causal mechanisms: it cannot determine whether lower X3 scores cause lower Y scores, or whether both reflect a common underlying factor such as institutional under-resourcing of maritime safety management. Longitudinal studies tracking safety perception and incident rates before and after targeted SOP and curriculum interventions would substantially strengthen the causal warrant for the study's policy recommendations. Such studies would also enable evaluation of whether the competency gap narrows as regulatory requirements are internalized through training programs, providing empirical feedback on the effectiveness of intervention strategies. Finally, the rapid commercial evolution of solid-state battery technology — with successive product generations altering energy density, thermal management characteristics, and failure mode distributions — necessitates regular review and updating of the ISO 31000 risk matrix as operational incident data accumulate, ensuring that the risk assessment framework remains calibrated to the actual battery technologies in circulation rather than to the specifications of early commercial models.

The Padang–Mentawai route was selected for its operational criticality and environmental distinctiveness, but the findings cannot be generalized to other domestic Indonesian ferry routes without comparable empirical investigation. The cross-sectional design precludes causal inference about the relationship between SOP implementation and safety outcomes. Future research should replicate the mixed-method risk assessment protocol on high-traffic routes including Merak–Bakauheni and Ketapang–Gilimanuk, where EV volumes are substantially higher. Longitudinal studies tracking the impact of SOP and curriculum interventions on risk indicator distributions would substantially strengthen the evidence base for the policy recommendations offered here. The rapid commercial evolution of solid-state battery technology — with successive generations altering energy density, thermal management characteristics, and failure modes — also necessitates regular updating of the risk assessment framework as empirical incident data accumulate.

IV CONCLUSION

This study has provided the first empirically grounded, mixed-method risk assessment of solid-state EV cargo stowage and fire mitigation capacity on the Padang–Mentawai ASDP ferry route, drawing on the perspectives of 60 maritime stakeholders across three institutional groups. The findings demonstrate that while regulatory awareness is relatively high, operational safety performance is constrained by a composite set of structural gaps: insufficient deck infrastructure for EV zone designation and thermal monitoring, systematic competency deficits among seafarers in thermal runaway management, and coordination failures across the regulatory and operational interface governing EV loading decisions. Multiple regression analysis confirms that fire mitigation human resource capacity is the stronger predictor of maritime safety perception, underscoring the primacy of training investment in any viable improvement strategy. The study contributes an ISO 31000-based adaptive risk assessment model and a concrete set of SOP and curriculum development recommendations, offering a replicable framework for EV fire safety governance on Indonesia's broader domestic ferry network as solid-state battery vehicles enter the mainstream of the national vehicle fleet.

REFERENCES

[1] S. Lee, D. Choi, Y. Jeong, M. Moon, H. Kwon, K. Han, H. Kim, H. Im, Y. Park, D. Shin, and G. Gwak, "Assessing fire dynamics and suppression techniques in electric vehicles at different states of charge: Implications for maritime safety," *Case Studies in Thermal Engineering*, vol. 64, 2024, doi: 10.1016/j.csite.2024.105474.

[2] Government of Indonesia, *Presidential Regulation No. 79 of 2023 on the Development of Electric Vehicle Ecosystems*, Jakarta: State Secretariat of the Republic of Indonesia, 2023.

[3] X. Zhang, et al., "Solid-state batteries for electric vehicles," *Energy Storage Materials*, vol. 45, pp. 102–115, 2022, doi: 10.1016/j.est.2022.01.012.

[4] X. Zhang, et al., "Impact of ventilation strategies on the evolution of electric vehicle fire characteristics in ships," *Ocean Engineering*, vol. 317, p. 120080, 2025, doi: 10.1016/j.oceaneng.2025.120080.

[5] T. Ayci, B. Barlas, and A. I. Olcer, "Evaluation on fire incident of electric vehicle spaces onboard ferries with using fire dynamics simulations," *Journal of Thermal Engineering*, vol. 11, no. 2, pp. 434–447, 2025, doi: 10.14744/thermal.0000925.

[6] Directorate General of Land Transportation, *Circular Letter SE-DRJD No. 7 of 2024 on Procedures for Loading Battery-Based Electric Vehicles on Ferry Vessels During the 2024 Eid al-Fitr Transport Period*, Jakarta: Ministry of Transportation of the Republic of Indonesia, 2024.

[7] Directorate General of Sea Transportation, *Circular Letter SE-DJPL No. 12 of 2024 on Handling of Indonesian-Flagged Vessels Transporting Electric Vehicles*, Jakarta: Ministry of Transportation of the Republic of Indonesia, 2024.

[8] I.-S. Mok, E. D'Agostini, and D.-K. Ryoo, "A validation study of ISM Code's continual effectiveness through a multilateral comparative analysis of maritime accidents in Korean waters," *Journal of Navigation*, vol. 76, no. 1, pp. 77–90, 2023, doi: 10.1017/S0373463322000571.

[9] D. H. Waskito, R. E. Kurt, A. P. Gusti, and L. P. Bowo, "Assessing the risk of transporting battery electric vehicles through water transportation modes by integrating system theory and Bayesian Network approach," *Ocean Engineering*, vol. 341, 2025, doi: 10.1016/j.oceaneng.2025.122606.

[10] S. Fu, Z. Sun, C. Jiang, Y. Hao, and W. Mao, "An integrated risk assessment framework for fire accidents on passenger ships," *Ocean Engineering*, vol. 343, 2026, doi: 10.1016/j.oceaneng.2025.123290.

[11] K. Shi, S. Fan, J. Weng, and Z. Yang, "Seafarer competency analysis: Data-driven model in restricted waters using Bayesian networks," *Ocean Engineering*, vol. 311, 2024, doi: 10.1016/j.oceaneng.2024.119001.

[12] M. H. Dewan and R. Godina, "Roles and challenges of seafarers for implementation of energy efficiency operational measures onboard ships," *Marine Policy*, vol. 155, 2023, doi: 10.1016/j.marpol.2023.105746.

[13] J. M. Pérez-Canosa and J. A. Orosa, "A new methodology for optimization of lashing lines in the securing arrangement of non-standardized cargo on ships," *Applied Sciences (Switzerland)*, vol. 14, no. 23, 2024, doi: 10.3390/app142311442.

[14] T. Peša, M. Krčum, G. Kero, and J. Šoda, "Ferry electrification energy demand and particle swarm optimization charging scheduling model parameters analysis," *Applied Sciences (Switzerland)*, vol. 15, no. 6, 2025, doi: 10.3390/app15063002.

[15] J. R. K. Bokau, R. Samad, Y. Park, and D. Kim, "From managing risk to reality: A case of maritime safety in Makassar Port, Indonesia using FRAM and AIS data analysis," *Ocean Engineering*, vol. 339, 2025, doi: 10.1016/j.oceaneng.2025.122012.

[16] International Organization for Standardization, *ISO 31000:2018 Risk Management — Guidelines*, Geneva: ISO, 2018.

[17] G. Zhao, X. Xie, Y. Wang, S. Liu, P. Jones, and C. Lopez, "Barrier analysis to improve big data analytics capability of the maritime industry: A mixed-method approach," *Technological Forecasting and Social Change*, vol. 203, 2024, doi: 10.1016/j.techfore.2024.123345.

[18] J. W. Creswell and C. N. Poth, *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, 4th ed. Thousand Oaks, CA: Sage, 2018.

[19] B. Miles, M. Huberman, and J. Saldaña, *Qualitative Data Analysis: A Methods Sourcebook*, 3rd ed. Thousand Oaks, CA: Sage, 2014.

[20] R. K. Yin, *Case Study Research and Applications: Design and Methods*, 6th ed. Thousand Oaks, CA: Sage, 2018.

[21] T. Pitana, M. K. Y. H. Soewirjo, N. Siswantoro, and A. Nurwahyudy, "Simulation of an electric vehicle fire on a ro-ro ferry," *Journal of Applied Engineering Science*, vol. 23, no. 1, pp. 45–55, 2025, doi: 10.5937/jaes23-50123.

[22] M. N. Rudijanto, "Regulatory gaps and the emerging risk of electric vehicle battery fires in Indonesia," *Jurnal Ilmu Hukum dan Kebijakan*, vol. 7, no. 1, pp. 89–104, 2024.

[23] M. B. Simanjuntak, Z. Rafli, and S. R. Utami, "Multiliteracy framework for maritime English communication: Enhancing proficiency in operational settings," *TransNav*, vol. 19, no. 4, pp. 1171–1178, 2025, doi: 10.12716/1001.19.04.14.

[24] International Maritime Organization, *SOLAS Consolidated Edition*, London: IMO, 2020.

[25] P. Hopkin, *Fundamentals of Risk Management*, 5th ed. London: Kogan Page, 2020.