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Identifying Risk Influencing Factors Related to Alternative Fuels in Winter Navigation

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Abstracts- The maritime sector is urgently transitioning toward alternative marine fuels to mitigate climate change; however, the operational viability of these solutions in harsh environments remains a critical gap in current research. While these fuels show promise for global decarbonization, their adoption in ice-covered seas, such as the Finnish-Swedish winter navigation zone, is complicated by extreme environmental conditions. This study identifies the critical risk factors associated with Liquefied Natural Gas (LNG), biofuels, methanol, hydrogen, ammonia, and nuclear power, under these specific winter navigation conditions. A systematic literature review is conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method to identify the risks associated with each energy carrier. Subsequently, principles of System-Theoretic Process Analysis (STPA) are applied to categorize these risks into scenario-based losses, accidents, hazards, and causal factors. The analysis reveals that the harsh winter environment acts as an active hazard multiplier, triggering emergent vulnerabilities that are absent in standard open-water operations. Consequently, the results suggest that, despite their potential, current alternative marine fuel solutions require targeted, region-specific safety adaptations before widespread deployment in the Northern Baltic Sea.
Keywords: Alternative fuels, winter navigation, PRISMA, safety, risk

1. Introduction

The growing concern over greenhouse gas (GHG) emissions has intensified due to rising energy consumption, particularly in maritime traffic. In 2020, the shipping industry emitted 706 million tonnes of Carbon dioxide CO2, accounting for approximately 3% of global human-caused emissions (IEA, 2022). In response to the threats of emissions on human health and the environment (Deshmukh et al., 2023; IMO, 2018) the maritime industry has focused on the development of new technologies and the use of alternative fuels with low or zero carbon emissions, such as Methanol, LNG, and Biofuels, Hydrogen, Ammonia, and Nuclear (Jovanović et al., 2022). Furthermore, different strategies and plans, such as the European Green Deal, EU Strategy for the Baltic Sea Region (European Commission, 2021), GHG emission reduction plans (MEPC, 2023) and Energy transition outlook (DNV, 2020) has been proposed by different regulatory bodies to reduce emissions and enhance maritime sustainability. However, a critical gap remains in understanding the operational feasibility and safety of these fuels in harsh environments. The integration of alternative fuels under severe winter conditions and ice navigation poses unique challenges that have not yet been fully explored. Addressing these specific risk factors is essential to ensure that the decarbonization goals outlined in the European Green Deal do not compromise maritime safety.

The use of alternative fuels can reduce emissions, thereby minimizing the environmental impact. However, adopting these fuels in winter conditions may also introduce emergent risks. During winter, the Baltic Sea experiences complex sea ice, and long periods of darkness, which makes navigation unsafe and unpredictable for ships (Valdez Banda et al., 2015). Consequently, it is crucial to identify and mitigate the risks systematically.

In the context of systematic risk assessment maritime domain, substantial research has addressed the Risk Influencing Factors (RIFs) associated with alternative fuels (Brynolf et al., 2014; Foretich et al., 2021), and winter navigation (Baksh et al., 2018; Valdez Banda et al., 2015). However, while some studies focus on the intersection (Lehtola et al., 2020; PAME, 2019; Yoo et al., 2020), no prior study systematically identifies alternative fuel RIFs in winter.

For such reviews, the PRISMA methodology has been increasingly used across various scientific domains due to its emphasis on transparency and completeness (Moher et al., 2010). Despite these advantages, PRISMA has not yet been applied to identify RIFs in this intersection. Therefore, this study aims to bridge this gap by identifying critical RIFs through a PRISMA-based SLR focused on the intersection of alternative fuels and winter navigation. The rest of the paper is structured as follows: Section 2 provides background on SysML, and Section 3 details the proposed methodology. Section 3 presents the results, and Section 4 discusses them. Finally, Section 4 concludes with key findings.

2. Methodology

Fig.1 illustrates a structured method for identifying and categorizing RIFs in complex systems to support risk assessment and decision-making.

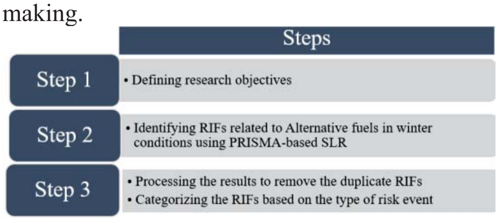

Fig.1 The framework of the methodology

Step 1: The initial phase focused on defining the research objectives and constructing a search strategy to guide the study. This process followed the standard PRISMA flow, which systematically moves through four distinct phases: Identification of records from databases, Screening of titles and abstracts, assessment of Eligibility based on full-text review, and final Inclusion of relevant studies.

Step 2: The second step employed the PRISMA-based SLR guidelines to identify RIFs. Using the PRISMA four-stage process, the literature was filtered to isolate studies relevant to specific alternative fuels, including LNG, biofuels, methanol, hydrogen, ammonia, and nuclear. This phase aimed to extract raw risk data directly associated with the operational challenges of these fuels in winter conditions.

Step 3: The final step synthesized the extracted data by categorizing the RIFs according to the STPA framework The risks were mapped into a hierarchical structure comprising High-level Causal Factors, Accidents, Hazards, and Losses.

3. Results

Step 1: In the identification phase, Scopus and Web of Science were selected for their broad coverage of peer-reviewed maritime research. Keywords were combined using Boolean operators to form three search streams: Winter Navigation (WN), Alternative Fuels (AF), and WN-AF as shown in Table 1. To systematically identify relevant literature, Boolean operators were applied across the four main domains: Ship, Risk, Winter navigation, and Alternative fuels. Specifically, the "OR" command was used within each individual row to capture synonyms and term variations (e.g., "Ship*" OR "vessel"), while the "AND" command was used to combine the different rows together. This logical combination ensured the search results exclusively isolated studies located at the precise intersection of all four concepts.

Table 1 Keywords related to the study

Ship	"Ship*", "vessel"
Risk	"risk*", "hazards*", "failure", "accidents", "incident", "safety"
Winter navigation	"winter navigat*", "arctic navigat*", "ice navigat*", "ice", "winter", "arctic"
Alternative fuels	"alternative fuel*", "green fuel*", "advanced fuel", "zero emission", "renewable", "green", "clean fuel", "methanol", "biofuel", "liquefied natural gas", LNG, "ammonia", "hydrogen", "electricity", "nuclear"

Duplicates were removed using EndNote and manual checks to ensure a clean dataset.

During screening, strict inclusion criteria were applied: only English, peer-reviewed journals, conference papers, and books were considered. Titles and abstracts were reviewed to exclude studies not addressing safety or operational aspects. In the eligibility phase, full texts were assessed for their ability to provide specific risk factors. Studies lacking risk analysis or winter context were excluded with documented reasons. This process resulted in 17 studies included for the WN-AF domain, from which RIFs were extracted (Fig. 2).

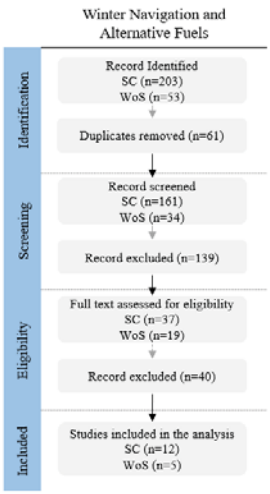

Fig. 2 **S**earch **r**esults in Web of Science and Scopus

Step2: Winter navigation presents several causal factors that increase the risks of using alternative fuels. Table 2 shows the RIFs related to using alternative fuels for winter navigation.

Using LNG in winter navigation introduces additional and higher risks than open-water sailing. Harsh conditions, like extreme cold conditions (Ding et al., 2020) and extreme cold (Katysheva, 2018), turn normally manageable situations into major operational failures. For example, the constant shock of ice accumulation and extreme cold put severe physical stress on the ship's engines and equipment (Gaspar et al., 2014) potentially leading to fires, explosions (Nubli et al., 2020), or collisions (Shaposhnikov et al., 2014; Yeun et al., 2015). Furthermore, if an LNG leaks, the extreme cold changes how the gas acts. Instead of warming up and floating away quickly, the leaked gas forms a thick, freezing cloud that stays trapped close to the deck (Aesoy et al., 2013). This vapor cloud, when mixed with air, can cause asphyxiation (Aronsson, 2012). or if exposed to an ignition source, can lead to fire and explosion. These accidents could then lead to human injuries or loss of life (Iannaccone et al., 2020). Additionally, the heavy strain of ice-breaking causes the engines to burn fuel less efficiently; this releases more unburned methane (methane slip) into the air, contributing significantly to GHG emissions, leading to long-term environmental loss by exacerbating global warming (Aesoy et al., 2013). Moreover, the loss of a ship is a serious consequence that can occur following a collision with ice in icy waters (Wan et al., 2023). Such accidents may also cause cargo loss and hull damage, further escalating the financial and operational impact (Gagnon et al., 2017).

Using biofuels, such as biodiesel and bioethanol, introduces different risks in winter navigation compared to open-water operations. In temperate climates, these fuels flow smoothly through a ship's systems. The extreme cold weather may cause an increase in the viscosity and density of the fuel, particularly biodiesel, leading to its solidification (Mohd Noor et al., 2018). This solid fuel quickly clogs the ship's filters, blocking the normal flow of fuel and causing the engine to fail (á Lað et al., 2017). Furthermore, these harsh conditions can exacerbate operational challenges by causing incomplete combustion, as the cold temperatures affect the fuel's ability to ignite efficiently (Yacout et al., 2021). If these fuels spill into the harsh environment, especially bioethanol, they release harmful toxins (Bengtsson et al., 2014). For instance, leaking Zinc (Zn) into the air and icy water severely damages the environment and threatens human health (Yacout et al., 2021). Finally, burning these fuels in cold engines creates higher levels of nitrogen oxides (NOx); this pollution contaminates the water and air, leading to further environmental destruction and human injuries (Hsieh & Felby, 2017).

Using methanol presents unique hazards during winter navigation compared to normal open-water operations. In warmer climates, spilled methanol evaporates quickly, but in freezing conditions, the extreme cold drastically slows this process, causing vapor to accumulate in enclosed or poorly ventilated areas. Since crews seal ship ventilation tightly against the cold, leaking methanol vapor quickly accumulates indoors, severely increasing health risks through inhalation or skin contact (á Lað et al., 2017). Despite freezing temperatures, methanol's low flashpoint combined with dry, static-prone winter air keeps the risk of sudden fire or explosion extremely high, potentially leading to the loss of the vessel and human life (Yacout et al., 2021). Operationally, sub-zero temperatures prevent methanol from burning completely in the engines, which significantly increases greenhouse gas emissions (Cherniak et al., 2015). Finally, if methanol spills overboard, surface ice prevents it from diluting normally;

instead, the ice traps the chemicals, severely elevating toxicity levels for local marine life (Keyte et al., 2015).

For Hydrogen, its leakage is a critical precursor to the hazards. Due to hydrogen's high flammability and high diffusivity, any release can quickly form a hazardous mixture (Molkov, 2012). However, the dry, freezing air of winter generates high levels of static electricity, acting as an invisible ignition source, drastically increasing the chance of spark into a fire or explosion (Astbury & Hawksworth, 2007) resulting in human injuries or loss of life. Additionally, although hydrogen is carbon-free, its release indirectly affects atmospheric methane and ozone levels (Derwent et al., 2020). Furthermore, extreme winter weather introduces a severe mechanical hazard; specifically, ice accumulation can block ventilation outlets or pressure relief devices. Since hydrogen systems rely on venting systems to manage boil-off gas and pressure, ice obstructions can create a risk of trapped gas, potentially leading to tank overpressure accidents (CGA, 2014). Ultimately, these factors could lead to the loss of the ship or cargo, or cause severe damage to the hull (Cai et al., 2024).

Regarding Ammonia, in warm climates, its leaked gas is lighter than air and dissipates safely upwards. However, in freezing winter air, the leaked gas rapidly condenses into a dense, heavy vapor cloud that loses its buoyancy and sinks directly to the deck level (Nowatzki, 2008). This cold-induced change creates a severe, localized toxic trap, increasing the immediate threat of crew asphyxiation and injuries (Council, 2003). Furthermore, while ammonia inherently has a high auto-ignition temperature, sub-zero conditions severely worsen this trait, leading to critical combustion instability and engine failures (Brohi, 2014; DNV.GL, 2019). The extreme cold and constant physical stress of winter also accelerate the failure of ship equipment already weakened by ammonia's highly corrosive nature (Council, 2003). Finally, the inability of engines to burn ammonia efficiently results in higher emissions of acidic pollution (NOx/SOx), causing environmental damage to the sensitive winter ecosystem (Makhlouf et al., 2015).

In ice-free waters, nuclear reactors safely and continuously draw cooling water through the ship's sea chests. However, freezing winter conditions introduce the unique threat of ice ingestion; ice chunks and freezing water physically block these intakes, causing a sudden and dangerous lack of cooling water (Hirdaris et al., 2014). This cold-weather blockage forces an immediate emergency reactor shutdown, and if safety barriers fail under the stress, it rapidly escalates into a catastrophic fire or explosion (Hirdaris et al., 2014). Furthermore, while any radioactive leak is dangerous, a spill in a frozen environment is uniquely devastating. The surface ice traps the non-biodegradable radioactive waste, causing it to persist and accumulate in a concentrated area rather than diluting into the open ocean (Fu et al., 2021). Ultimately, this localized accumulation leads to severe, long-term contamination of the Arctic food chain, catastrophic environmental damage, human injuries, and the total loss of the ship.

Step 3, As illustrated in Table 2, the extracted RIFs were systematically categorized using the STPA principals into Losses, Accidents, Hazards, and High-level Causal Factors. This process involved first consolidating the raw data to eliminate duplicates across the literature.

4. Discussion

A key strength of this study is integrating PRISMA with STPA to address a fragmented research domain. While literature on alternative marine fuels is extensive, safety evidence for winter conditions is limited. PRISMA provides a transparent and reproducible framework for identifying and filtering relevant studies, thereby minimizing selection bias and ensuring a comprehensive evidence base. Moreover, STPA serves not as a full hazard analysis but as a conceptual framework for structuring and interpreting the RIFs. STPA hierarchical logic systematically organizes extracted risks to reveal their interrelationships. This structured approach enables a shift from viewing risks as isolated failures to understanding them as part of a dynamic control system. Furthermore, the combined approach facilitated data collection and a coherent, system-oriented interpretation of how environmental conditions influence vessel safety when using alternative fuels.

The findings reveal that environmental conditions play a central role in shaping risk pathways, not merely as external stressors but as active drivers of system behavior. Low-temperature environments influence the physical and chemical properties of alternative fuels, leading to hazards such as solidification, condensation, and impaired functionality of safety-critical components. These hazards are not isolated; rather, they are interconnected and can propagate across system levels, increasing the likelihood of severe accidents. This demonstrates that the risks associated with alternative fuels in winter conditions are fundamentally different from those observed under standard operating environments, as they emerge from the interaction between environmental factors and fuel characteristics.

Furthermore, this study's results highlight the differential risks posed by each alternative fuel under winter conditions, underscoring that no single fuel can be considered universally safe in icy environments. LNG, biofuels, methanol, hydrogen, ammonia, and nuclear power each exhibit distinct vulnerabilities, from physical stresses on engines and equipment to chemical hazards such as toxic or flammable vapors accumulating near the deck or within confined spaces. These findings demonstrate that extreme cold not only magnifies the inherent hazards of each fuel but also interacts with operational processes, such as ventilation, ice-breaking, and engine performance, creating cascading failure pathways. For instance, ice accumulation can obstruct critical safety systems, while low temperatures can prevent complete combustion or trap chemical leaks, thereby increasing both the likelihood and severity of accidents. The analysis also underscores the environmental implications of winter fuel use, as inefficient combustion and trapped spills contribute to greenhouse gas emissions and local ecological contamination. Collectively, these results reinforce that fuel-specific mitigation strategies must consider the complex interplay between environmental stressors, operational constraints, and fuel properties to prevent both human and environmental harm.

These insights are highly relevant for both industry and policy, particularly in the context of the ongoing maritime energy transition. While the adoption of alternative fuels is essential for reducing greenhouse gas emissions, their safe implementation requires a context-specific understanding of operational risks. The results of this study highlight the limitations of applying uniform safety standards across diverse environments and emphasize the need for region-specific adaptations, especially in ice-covered regions such as the Baltic Sea. From an environmental perspective, ensuring the safe use of these fuels is critical to prevent unintended consequences, including accidents and pollution in sensitive ecosystems. Therefore, a comprehensive understanding of fuel behaviour under extreme conditions is essential to ensure that the transition to sustainable shipping remains both effective and safe.

5. Conclusion

This study systematically addresses the critical safety gap at the intersection of maritime decarbonization and severe winter operations. By employing a PRISMA-based Systematic Literature Review, the research isolated 17 key studies that specifically investigate alternative fuels in ice conditions, revealing that current safety assessments often overlook the unique stressors of the Baltic environment. The subsequent STPA-based categorization demonstrates that "Harsh Environmental Conditions" act as a pervasive high-level causal factor, triggering distinct failure modes across all fuel types, from battery capacity loss and frozen hydrogen vents to the altered behavior of toxic ammonia vapors in cold air. Consequently, this research concludes that while the transition to alternative fuels is imperative for meeting the European Green Deal targets, it must be accompanied by region-specific winterization standards. Without these targeted safety protocols, the environmental benefits of green shipping may be compromised by the elevated risk of catastrophic accidents in the sensitive Baltic ecosystem.

For future work, conducting a comprehensive hazard analysis using methods such as the Functional Resonance Analysis Method (FRAM) or a full STPA approach would be valuable for systematically quantifying and tracing the complex interactions among environmental stressors, fuel properties, and operational processes. Such analyses could provide actionable insights for designing robust, winter-specific safety protocols for alternative fuels in maritime operations.

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Table 2 RIFs related to Alternative fuels in winter conditions

Alternative fuels	ID	Losses	ID	Accidents	ID	Hazards	ID	High-level Causal factors
LNG	L1	Human injuries	A1	Fire/Explosion	H1	Engine failure	HCF1	Harsh environmental condition (ice, extreme cold)
	L2	Loss of life	A2	Asphyxiation	H2	Vapor cloud formation		
	L3	Loss of ship	A3	GHG emission	H3	Methane slip	HCF2	LNG leakage
	L4	Loss of cargo	A4	Collision ship-ice				
	L5	Damage to the hull						
	L6	Environmental loss						
Biofuels (e.g., Biodiesel, Bioethanol)	L1	Human injuries	A1	Eutrophication	H1	Solidification	HCF1	Harsh environmental conditions (ice, extreme cold)
	L2	Environmental loss	A2	Engine failure	H2	Fuel filter clogging		
			A3	Acidification	H3	NOx emissions	HCF2	Biofuel release
					H4	Zn emissions		
					H5	Incomplete combustion		
Methanol	L1	Human injuries	A1	Fire/Explosion	H1	Accumulation of Methanol vapor	HCF1	Harsh environmental conditions (ice, extreme cold)
	L2	Loss of life	A2	GHG emission	H2	Incomplete combustion		
	L3	Loss of ship	A3	Methanol toxicity incidents	H3	Methanol's low flashpoint	HCF2	Methanol leakage
	L4	Environmental loss			H4	Volatile nature of Methanol		
Hydrogen	L1	Human injuries	A1	Fire/Explosion	H1	High flammability	HCF1	Harsh environmental conditions (ice, extreme cold)
	L2	Loss of life	A2	GHG emission	H2	High diffusivity (Rapid spread)		
	L3	Loss of ship					HCF2	Hydrogen leakage
	L4	Loss of cargo			H3	Tank Overpressure		
	L5	Damage to the hull						
	L6	Environmental loss						
Ammonia	L1	Human injuries	A1	Toxic vapor release	H1	Vapor cloud formation	HCF1	Harsh environmental conditions (ice, extreme cold)
	L6	Environmental loss	A2	Acidic pollution (NOx/SOx)	H2	high auto-ignition temperature		
			A3	Crew Asphyxiation (Deck level)	H3	Combustion instability	HCF2	Ammonia leakage
					H4	Corrosive		

Table 3-continued. RIFs related to Alternative fuels in winter conditions

Alternative fuels	ID	Losses	ID	Accidents	ID	Hazards	ID	High-level Causal factors
Ammonia	L1	Human injuries	A1	Toxic vapor release	H1	Vapor cloud formation	HCF1	Harsh environmental conditions (ice, extreme cold)
	L6	Environment al loss	A2	Acidic pollution (NOx/SOx)	H2	high auto-ignition temperature		
			A3	Crew Asphyxiation (Deck level)	H3	Combustion instability	HCF2	Ammonia leakage
					H4	Corrosive		
Nuclear	L1	Human injuries	A1	Fire/Explosion	H1	Radioactive waste accumulation	HCF1	Harsh environmental conditions (ice, extreme cold)
	L3	Loss of ship	A2	Food chain contamination	H2	Environmental persistence (non-biodegradable)		
	L6	Environment al loss	A3	Reactor Shutdown	H3	Cooling water starvation	HCF2	Radioactive leakage

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