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Alternative Fuels for Shipping: Implications for Seafarers' Occupational Safety and Health

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ABSTRACT

The maritime sector is in the process of shifting towards alternative fuels in order to minimize emissions of greenhouse gases (GHG) and to improve environmental footprint. This paper investigates the implications of alternative fuel solutions such as hydrogen, ammonia and nuclear propulsion on the wider issue of seafarers' occupational safety and health (OSH), the paper is based on lessons learned from Sweden's experience in utilizing battery powered vessels. Although, lithium-ion batteries effectively lower emissions and increase operating efficiency, they also present significant OSH risks, such as fire hazards or chemical exposure, and technostress; therefore, a complex regulatory framework and shortages in infrastructure capabilities must be considered. Benefits come with new risks; for example, hydrogen has high energy density and zero emissions but there is high flammability risk, which necessitates complex storage solutions and safety requirements. Easily stored and transported, ammonia poses toxicity hazards requiring stringent handling procedures. Nuclear propulsion, a proven technology in military and icebreaker vessels, is viewed as quite promising for deep-sea shipping because of its emissions-free nature, but there are important obstacles to overcome; indicative examples include,but are not limited to, radiation safety risks, waste management and societal acceptance. The *M/S Aurora of Helsingborg*, Sweden's first battery-operated ferry, provided certain guiding lessons on the necessity of seafarer involvement and extensive training to safely handle new and future means of propulsion; the need for regulatory changes/adaptation is also standing out. The analysis highlights the importance of risk assessment, collaboration among different actors involved in the shipping sector, and international co-orchestration in relation to the transition to alternative fuels, and towards a more sustainable maritime industry, with a focus on the overall seafarers' welfare.

Keywords: Alternative fuels, Maritime shipping, Seafarers, Occupational safety and health

INTRODUCTION

The world needs to take urgent action to tackle the notorious and multi-level phenomenon of "climate change" and global warming. To contribute to that effort, the global shipping industry is implementing an intense (and with a rather quick pace) transition to alternative fuels in order to meet the ambitious greenhouse gas (GHG) emission reduction targets set by international agreements such as the Paris Agreement and the

International Maritime Organization's (IMO) revised GHG strategy. This revised IMO GHG strategy includes an enhanced common ambition to reach net-zero GHG emissions from international shipping by or around 2050, a commitment to make sure an uptake of alternative zero and near-zero GHG fuels by 2030, in addition to indicative check-points for 2030 and 2040 (IMO, 2022). This shift primarily motivated by the much-required decarbonization of shipping, which represents about 3% of the world's global greenhouse gas (GHG) emissions and adherence to the net-zero emissions by 2050 (The Seafarers Charity, 2024). Ensuring safety is of paramount importance in achieving the successful and timely roll out of new fuels; effective development of safety regulations and guidelines is necessary in order to move towards widespread commercial use. At the same time, although alternative fuels such as hydrogen, ammonia, and even nuclear propulsion can improve the related environmental footprint, they will generate new and complicated occupational safety and health (OSH) hazards for seafarers. Building on the knowledge gained from Sweden's first battery-operated ship, this paper investigates the OSH risks of these new fuels and advocates regulatory innovation, on-the-job training and facilitate dialogue between stakeholders to ensure a safe and fair transition for marine workers and seafarers in particular (Lagdami & Baig, 2024).

DECARBONIZATION AND THE ADVANCE FOR ALTERNATIVE FUELS

Decarbonizing shipping is not only a technical challenge, but also a systemic transformation that touches every aspect of maritime operations. Introduction and safe utilisation of the so-called "zero carbon fuels" has now become a pressing necessity. Hydrogen, ammonia, nuclear propulsion, and battery-electric technologies each represent particular pathways for reducing emissions. Their uptake is driven by considerations such as fuel availability, preparedness of infrastructure, extent/complexity of the regulatory framework, social acceptance, and, most importantly, the ability of seafarers to operate these systems safely (The Nautical Institute, 2024). Improving knowledge and skills relating to alternative fuels of seafarers and shore-based personnel is a requirement and a future training objective and activity, which is developed under a holistic approach and including a very strong practical element. This will play an essential role towards ensuring that seafarers will effectively/safely handle all these new types of marine fuels/technologies (WMU News, 2025).

Hydrogen is being viewed with growing interest as a very promising zero carbon fuel, with a high energy density and clean burning characteristics, water being the only emission at the point of use (Safety4Sea, 2024). Ammonia, created by combining hydrogen and nitrogen, is also attractive, as it can be stored and transported more easily than hydrogen, and does not generate carbon dioxide when it is burned (EMSA, 2023). Nuclear propulsion can be used for zero emissions over long periods, as it has been done for many decades on certain military vessels, as well as the icebreaker fleet (IMO Res. A.491(XII)). The battery-electric system, which is proven by Sweden's battery-powered ferries, is particularly well-suited for short-distance shipping and inland waterways, offering immediate reduction in local air pollution and GHG emissions.

Although having these advantages, the transfer from existing towards alternative/substitute fuels involves various challenges and complexities with respect to operations and safety hazards prevention. The unique physical and chemical characteristics of each of these technologies require new competencies and skills, mature technology applications, and strict safety procedures. Furthermore, consequences for seafarers' health and safety are of utmost importance and must be taken into account by policy makers, ship-owners, stakeholders and training institutions.

Alternative Fuels and OSH Implications

Hydrogen

Hydrogen is considered a promising fuel since its use has a high energy density and zero carbon emissions, offering notable potential for reducing the maritime industry's environmental impact (Bicer & Dincer, 2018). Nevertheless, its adoption introduces significant OSH issues, all of which need to be addressed to ensure seafarers' safety and wellbeing, especially during storage and bunkering activities, hydrogen's high flammability and low ignition, raises the risk of leaks and major accidents (Allal et al., 2019). Low density of the fuel calls for high-pressure or cryogenic storage facilities, which are complicated and prone to mechanical breakdown if improperly maintained. It is noteworthy that hydrogen can either be stored in very high-pressure arrangements (at the range of 350–700 bars tank pressure), or as a cryogenic liquid (–253 °C) at atmospheric pressure (WMU News, 2025).

Because hydrogen is colorless and odorless, leaks often go unnoticed, unless they are monitored by dedicated sensors, thus posing the risk of build-up occurring unnoticed and eventually leading to catastrophic outcomes. At the same time, there are potential health and safety risks for seafarers in terms of asphyxiation or burns from hydrogen leaks, necessitating specialized training in leak detection, emergency response, and the use of personal protective equipment (PPE) (Bach et al., 2020).

Both onshore and onboard hydrogen infrastructure are costly and must be adequately regulated. Although at the 10th session of the IMO subcommittee on Carriage of Cargoes and Containers (CCC 10) held from 16 to 20 September 2024, it was agreed to develop interim guidelines for the use of ammonia as fuel and to complete the work on interim guidelines for the use of hydrogen within current applicable regulations, ship-owners and seafarers are still struggling with the use of hydrogen (WMU News 2025). For seafarers, this requires adequate training in handling hydrogen, leak detection, and emergency response. Crew members must be familiar with "high pressure" storage systems, the use of PPE, and the procedures for isolating and ventilating affected areas in the event of a leak. The adoption of hydrogen as a marine fuel also requires new safety management systems and applications of sophisticated monitoring solutions on board ships (Lighthouse, 2023).

Ammonia

Ammonia is attracting significant interest as an alternative fuel, due to its relative ease of storage and transportation compared to hydrogen (Brynolf, 2014). It can be liquefied either by low to medium pressure, or by cooling it down to –34°C and forming a noncryogenic liquid. Its potential to reduce GHG emissions makes it a great option for decarbonizing the maritime sector. However, the high potential of ammonia's toxicity presents significant OSH challenges that demand stringent safety precautions. Ammonia's rather high toxicity (in case of a leak) is creating the need for establishing related hazardous and toxic zones onboard ships, as well as using PPE of special/enhanced design for entry and operation within these zones (WMU News, 2025). Ammonia may lead to serious respiratory problems, skin burns, and neurological impairment, potentially endangering seafarers, for example, when handling or conducting maintenance or in case there is a leakage (Brynolf et al., 2014). Effective ventilation systems, gas detection technologies, and PPE are critical to minimizing these risks, alongside comprehensive training in ammonia-specific safety protocols (Allal et al., 2019).

On 21 December 2024, the IMO's Maritime Safety Committee (MSC) adopted at its 102nd session the MSC. 1/Circ. 1687 provisional Interim Guidelines for the Safety of Ships using Ammonia as a fuel. This is indicative of the increasing interest in ammonia as a marine fuel in view of decarbonization targets and the demand for a methodical, risk-based approach to its safe application. Seafarers working on board ammonia-fueled ships must have undergone extensive training in handling dangerous chemicals, using gas-tight protective equipment, and operating emergency ventilation and decontamination. Ammonia release, spills, and emergency response planning must be expanded to include potential exposure and medical treatment (EMSA, 2023). Along with these, rigorous safety measures and daily risk assessment will be necessary to safeguard the health of the crews and to minimize the pollution of the environment.

Nuclear Propulsion

Applied in naval surface vessels, submarines, and icebreakers, nuclear propulsion presents great promise for deep-sea commerce because of its zero-emission profiles and high energy efficiency (Bicer & Dincer, 2018). Long-distance routes fit well the specific technology application, since it allows ships to travel enormous distances without the need of a refueling. Its use by commercial shipping, however, also generates serious OSH problems that need to be closely handled. Mariners who are exposed to radiation either during reactor maintenance or in the case of accidents will face serious long-term health risks, including higher susceptibility to cancer tumors or organ damage.

To avoid these potential problems, specific instruction and training activities relating to radiation safety, readiness, and reactor operations will be needed. Furthermore, another issue of concern is the safe disposal of radioactive waste; improper management of this such waste could lead to environmental degradation with resultant major impacts on the health of coastal residents and seafarers (Al-Enazi et al., 2021). Public doubts and perception, as well as strict/complex regulations adds more challenges to the adoption of this technology application and calls for an open risk communication and enhanced regulatory framework. Past experience illustrates the potential adverse consequences of a maritime nuclear accident, from environmental pollution to life or reputational loss, this requires strong safety cultures, and open risk communication.

BATTERY-POWERED VESSELS: LESSONS LEARNT FROM SWEDEN

Battery-electric and hybrid propulsion systems have gained market share, especially in short-distance ferries. Sweden's adoption of battery-powered vessels such as the *M/S Aurora af Helsingborg*, illustrates both the environmental benefits and OSH challenges of substitute fuels.

Converted to hybrid battery operation in 2018, the *M/S Aurora* reduced the CO_2emissions by 37,000 tons while substantially reducing noise and vibration, providing increased safety and reduced OSH to seafarers, as well as comfortable working conditions (Lagdami, 2023). On the other hand, the journey toward using lithium-ion batteries also brings a number of OSH challenges that need to be managed effectively. This paper reports on a case study that has been carried out to investigate how the transition to this new type of technology as an alternative to fuels is working in Sweden.

METHODOLOGY

To explore the OSH consequences of using alternative fuels in maritime operations, this research considers a qualitative exploratory approach and conducts an empirical investigation with respect to Sweden's experience of using Lithium-ion batteries on ferries. At the centrepiece of this, *M/S Aurora* exemplifies best practices in integrating battery systems. The ferry has 640 batteries, housed in reinforced containers and charged via automated systems, which demonstrates engineering innovation. It is also a case study that provides a detailed and contextualized account of the OSH issues arising from alternatives to traditional fuels. The case of *M/S Aurora* exemplifies the operational, regulatory, and training challenges faced when deploying new energy sources. The case study approach helps identify learned lessons that can be transferable and applied to hydrogen, ammonia, methanol, or nuclear propulsion.

FINDINGS OF THE FIELD STUDY

According to the field study conducted by the authors, three key findings emerged as best practices for using lithium-ion batteries as alternatives to traditional fuels: 1) Risk assessment and preventive measures, 2) emergency preparedness and transparent incident reporting, and 3) training and continuous learning. Before exploring these best practices, an analysis of the occupational safety and health (OSH) risks associated with lithium-ion batteries was conducted in the following section.

Lithium-Ion Battery's OSH Risks

A primary OSH concern associated with lithium-ion battery systems is the risk of thermal runaway. Overheating caused by damaged battery cells can lead to fires or explosions. Notably, an incident involving the Norwegian ship *Samudri Bem Explorer* exemplified these risks, as a battery bank overheated and triggered a fire, highlighting the severity of such events (SipInsight, 2021). In addition to thermal risks, the release of toxic gases during battery fires presents significant health hazards. This situation necessitates the use of advanced fire suppression and ventilation systems to protect crew members (DNV-GL, 2019). Chemical exposure is another critical issue, as lithium-ion batteries contain hazardous substances such as lithium, nickel, and manganese. These materials can be toxic or carcinogenic, with manganese exposure in particular posing risks of chronic poisoning that can affect the central nervous system and lungs (Vimmerstedt et al., 1995). Therefore, seafarers face risks not only during routine battery maintenance but also in the event of cell containment failure, requiring strict handling protocols and the use of PPE.

Furthermore, the adoption of battery systems introduces the so-called technostress, which is a form of stress resulting from the adoption of new technologies. Regarding this particular aspect, seafarers working on board *Aurora* reported increased cognitive workloads and the need to acquire and learn new skills due to techno-overload and the complexity of new systems (Lagdami, 2023). Initial skepticism regarding battery systems was prevalent, driven by unfamiliarity and concerns about safety. Nevertheless, proper training in high-voltage systems and thermal runaway prevention, combined with seafarers' involvement in design discussion, significantly reduced stress and increased confidence in managing the impact of the technology (Lagdami, 2023). These findings demonstrate the value of education and engagement in mitigating OSH challenges during the adoption of alternative fuels.

BEST PRACTICES TO MANAGE OSH

The Case of Using Battery Systems On-Board and What Was Learned in Sweden

Risk Assessment and Preventive Measures

M/S Aurora's strong risk management assessment greatly contributes to the success of its transition from conventional fuel to battery-electric power. Stress testing of battery suppliers, electromagnetic compatibility (EMC) assessments, and scenario-based training have fostered a culture of prevention. Preventive strategies include emergency cut-off systems, structural containment, and battery compartment cooling systems. These measures, combined with a strong safety culture and open communication, ensure high resilience against potential hazards.

Emergency Preparedness and Incident Reporting

Lithium-ion batteries present hazards such as thermal runaway, chemical exposure, fire, and toxic gas emissions. Their high energy density makes them efficient but also potentially dangerous. Effective emergency protocols are vital for managing battery-related incidents. *M/S Aurora* is equipped with systems to flood battery containers in case of fire and conducts regular emergency drills. A no-blame reporting culture allows seafarers to raise safety concerns freely, reinforcing continuous improvement. Although no major incidents have occurred, the crew remains vigilant, acknowledging that unforeseen risks are always possible.

Training and Continuous Learning

Training is the cornerstone of OSH in the context of technological change. The *M/S Aurora* crew received specialized instruction in high-voltage handling, electrical firefighting, and thermal runaway prevention. The use of simulation tools, hands-on workshops, and daily briefings fosters a learning-by-doing environment. However, some crew members noted the need for ongoing training to retain and deepen their knowledge, especially as battery technologies evolve.

Discussion and Recommendations for a Just Transition

The case study of the *M/S Aurora of Helsingborg* provides critical insights into the management of occupational safety and health (OSH) during the transition to alternative fuels in shipping industry. The ferry's conversion to hybrid battery power in 2018 highlighted the importance of integrating seafarers' experiences into both the design and planning processes. Involving crew members in these discussions helped reduce skepticism and technostress while also fostering a sense of ownership and confidence in the new technology (Lagdami, 2024). This participatory approach ensured that the practical knowledge of those working on board informed the conversion and design of the ship, thereby anticipating and mitigating potential OSH challenges early in the process.

A key factor contributing to the success of the Aurora's transition was the provision of comprehensive training for seafarers. Instructions covered high-voltage systems, thermal runaway prevention, and firefighting protocols, ensuring that the crew was well-prepared for latest operational demands of utilized battery technology (Lagdami, 2023). Collaboration with manufacturers and classification societies, as well as adherence to guidelines established by the Swedish Transport Agency, provided a robust regulatory framework that reinforced safety standards for battery-powered vessels (Swedish Transport Agency, 2021).

Regular risk assessments played a central role in identifying hazards such as thermal runaway and chemical exposure. These assessments enabled the implementation of preventive measures, including the use of cooling systems, personal protective equipment (PPE), and automated shutdown systems. The operator's cooperation with classification societies, technology developers, and unions led to the development of comprehensive safety protocols that addressed both technical and human factors (Lagdami, 2024). The lessons learned from this process are directly applicable to the adoption of hydrogen, ammonia, and nuclear propulsion, underscoring the necessity for seafarer-centered policies, robust training, and international coordination to effectively manage OSH risks.

To ensure a fair and safe transition to alternative fuels, several approaches are recommended, drawing from the *Aurora*'s battery experience. First, OSH concerns such as flammability, toxicity, and emergency response must be addressed. The International Labour Organization (ILO) points out that there are specific rules for hydrogen, ammonia, and nuclear propulsion, including standardized risk assessments, emergency procedures, PPE requirements, and clear responsibilities for ship-owners and seafarers (ILO). Comprehensive training is essential to enable seafarers with the proper skills needed to safely manage new technologies. Training should encompass hazard detection, ammonia handling, hydrogen leak management, and nuclear safety, with frequent updates and practical exercises to prepare crews for real-world events (Lagdami, 2023). Furthermore, the development of safety management protocols that involve seafarers in the research and implementation process is vital for ensuring a just transition. As demonstrated by the *Aurora* project, participatory approaches significantly improve safety outcomes and foster acceptance of new technologies (Swedish Transport Agency, 2021).

CONCLUSION

The transition to alternative fuels is imperative for decarbonizing the maritime industry; however, it introduces substantial occupational safety and health (OSH) challenges for seafarers. Seafarers with already available background in handling gases (i.e. LNG/LPG, or ammonia) may require less upskilling compared to others; however, even experienced seafarers will need to enhance their understanding of fuel-specific hazards and the effective use of new equipment or technology. Insights from Sweden's deployment of the *M/S Aurora af Helsingborg* illustrates the value of inclusive seafarer engagement, comprehensive training programs, and adaptive regulatory frameworks in managing emerging risks such as thermal runaway, chemical exposure, and technostress. While hydrogen, ammonia, and nuclear propulsion present significant environmental advantages, each technology necessitates tailored safety protocols to mitigate associated hazards-ranging from flammability and toxicity to radiation exposure.

To ensure a just and sustainable energy transition, the maritime sector must adopt coordinated legislative, educational, and cooperative strategies that safeguard the well-being of its workforce. These findings extend beyond maritime contexts, for example hydrogen requires stringent controls to prevent ignition; ammonia demands robust ventilation and protective measures to manage toxicity, and nuclear propulsion necessitates entirely new safety regimes concerning radiation protection, accident mitigation, and decommissioning. Furthermore, the integration of high-voltage energy storage systems and advanced fuel systems and technology introduces a multitude of operational complexities. Hydrogen and ammonia technologies will require innovations in high-pressure containment, leak detection, and ventilation, while nuclear propulsion will demand the importation of rigorous standards from the nuclear industry, possibly even a redefinition of crew certification and ship monitoring protocols. Across all propulsion systems, prioritizing seafarer safety through specialized training, resilient infrastructure, and transparent regulatory oversight remains non-negotiable.

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