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Operational and Human Dimensions of Wind-Assisted Propulsion Systems: A Systematic Review Informed by Newer Safety Paradigms

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The ongoing decarbonization of maritime transport has accelerated the implementation of Wind-Assisted Propulsion Systems (WAPS). While technical advantages have progressed rapidly, limited attention has been paid to the operational and human dimensions of WAPS. WAPS introduce novel operational demands, altered vessel dynamics, and new decision-making contexts that can be difficult to address within reactive, incident-based safety frameworks, on which current maritime competence frameworks largely rely. This paper presents a systematic literature review following the PRISMA guidelines addressing the operational and human dimensions of WAPS. It identifies and categorizes findings from 21 articles across four thematic areas: (1) institutional and regulatory framework for competence and training, (2) operational and work-related demands introduced by WAPS, (3) competence and skill requirements, and (4) training, learning and safety practice. The review shows that WAPS operations are characterized by increased operational variability, new navigational demands, and reliance on experience-based decision-making, while formal competence requirements and training provisions remain fragmented and underdeveloped. Understood in the light of newer safety paradigms (NSP), the results highlight the need for training and safety management approaches that support operational adaptation and learning under conditions of uncertainty

Keywords: Operational Adaptation, Newer Safety Paradigms, Maritime Competence, Wind-Assisted Propulsion Systems, Safety Management

1. Introduction

The implementation and use of Wind-Assisted Propulsion Systems (WAPS) have increased in recent years, following the International Maritime Organization's (IMO) revised strategy to achieve net-zero emissions by 2050 (IMO, 2023). Current research on WAPS has predominantly focused on technical development and performance. Comparatively, little attention has been given to the operational and human dimensions of WAPS. This study aims to summarize current literature on these dimensions and discuss their implications for maritime safety management.

2. Methodology

This paper presents a systematic literature review of publications addressing the operational and human dimensions related to the use of WAPS on maritime vessels. The review set out to identify publications related to competence requirements, training practices and operational aspects. The review process followed the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020* (Page et al., 2021). As supplementary material for this article, the full review documentation is made available on Open Science Framework. Files include PRISMA search protocol, PRISMA checklist, PRISMA flow diagram and an overview of all publications: **https://doi.org/10.17605/OSF.IO/3UKAS**

2.1. *Inclusion & Exclusion Criteria*

Publications for the review were included if they met the following criteria:

- Relevance: Addressing WAPS or hybrid/green propulsion technologies in maritime domain
- Focus: Operational and human dimensions of WAPS, including competence requirements, training practices and human aspects of ship operations.

- Publication Type: Scientific Publications, Regulatory- & Industrial Reports
- Language: English

Excluding criteria were defined as:

- Focused exclusively on technical aspects or engineering performance
- Full text not available

There was no restriction set regarding the timeframe to not accidentally exclude relevant publications from the initial search.

2.2. *Search Strategy & Information Sources*

The Search String was constructed as follows:

("Wind-assisted" OR "Wind Propulsion" OR WAPS OR "Green Technolog") AND (Ship* OR Vessel OR Maritim*) AND (Competenc* OR Navigat* OR Training OR "Human Factors" OR Operation* OR Resilience OR cognit* OR Safety* OR Risk OR Learning* OR Education)*

On 15th December 2025, the main search was performed on:

- SCOPUS: 256
- Web of Science: 142
- Academic Search Elite (EBSCOhost): 191

Across all databases, the search resulted in a total of 589 records, with additional 31 records identified through snowballing. After removing 155 duplicates, 465 records remained. After title and abstract screening, 205 records remained. Six of these records could not be retrieved in full text. Thus, 199 records were read in full text. Finally, a total of 21 publications were included in the qualitative synthesis.

2.3. *Qualitative Appraisal*

As the review included both peer-reviewed and non-peer reviewed publications, each included publication was critically assessed throughout the research process by the first author.

2.4. *Limitations of the Study*

This review is subjected to limitations, since the available evidence is scarce and heterogeneous, which limits the generalizability and certainty of the findings. Furthermore, the review process is subject to constraints. For instance, publications in other languages exist but have not been included. In addition, no formal assessment of reporting bias or sensitivity analysis was performed.

3. Results

The review identified operational and human aspects among five thematic levels related to WAPS.

(i). Institutional and Regulatory Framework for Competence & Training
(ii). Operational & Work-related Demands
(iii). Competence Requirements
(iv). Training and Learning
(v). Safety Considerations and Practices

First, the current maritime regulatory framework regarding WAPS is described, followed by the operational demands introduced. After that, the evolving competences needed for operational adaptation are outlined, before fields of training and learning as well as safety considerations and practices are presented.

3.1. *Institutional and Regulatory Framework for Competence & Training*

The literature describes the institutional and regulatory context for WAPS as evolving and insufficiently established, with several studies identifying gaps in standards, guidance and competence-related requirements. Studies point to a limited empirical evidence base, reflected in a lack of sea trials as well as limited practical and scientific knowledge (Rehmatulla et al., 2017; Rojon & Dieperink, 2014). This is further illustrated by reported gaps in third-party validation of results from early applications of WAPS, limited cooperation between technology providers, and a hesitant development of knowledge exchange platforms (Rojon & Dieperink, 2014).

In line with these observations, a lack of established standards related to competence development and safety for WAPS is highlighted (European Maritime Safety Agency [EMSA], 2023; Lamvik et al., 2025; Wang et al., 2025). In addition, Rieffel et al. (2025) points directly to the STCW-Convention, indicating that it does not include theoretical or practical competence requirements for WAPS.

Consistent with that, the IMO (2024) call for the development of specific guidelines for navigation and safety related to WAPS. Further, the IMO (2024) suggests that guidelines should align with existing safety standards and regulatory frameworks. This could potentially require revisions of current regulations.

Beyond the absence of established standards for competence development, the literature identifies several systemic challenges related to the integration of new technologies into existing maritime frameworks. Current regulatory and certification processes are described as involving complex adaptation processes when integrating new technologies into established maritime practices (Melnyk et al., 2024). As a result, competence development related to new technologies may be perceived as operationally demanding or difficult to implement within existing organizational and operational systems (Nelissen et al., 2016). Two of the included studies further indicate that requirements for additional competences are, in some cases, perceived negatively or approached with an emphasis on minimizing additional operational or organizational burden (Atkinson et al., 2018; IMO, 2024).

3.2. *Operational and Work-Related Demands of WAPS*

The literature describes operation of WAPS as associated with increased operational variability and decision-making demands, shaped by environmental conditions (Chou et al., 2021) and uncertainty due to limited operational experience and empirical evidence (Rojon & Dieperink, 2014). It is further outlined how WAPS introduce new navigational demands, caused by increased complexity of the vessel's behavior and maneuverability caused through the sails and coupled aerodynamic and hydrodynamic effects (Atkinson et al., 2018; Lamvik et al., 2025; Wang et al., 2025).

The literature documents varying approaches to control of WAPS, with different degrees of automation across system designs and operational contexts (Argyros, 2015). WAPS concepts are often thought of as predominantly automated (Nelissen et al., 2016). Industry-oriented guidance and reports emphasize automation as a means of simplifying operational demands (IMO, 2024). In line with this perspective, Bertram (2020) argues for implementation of robust and highly automated WAPS, particularly in the context of low-crew and smart ship developments.

At the same time, limitations to automation in practice are highlighted. Automatic control systems may be more constrained on smaller vessels, where manual handling remains common (IMO, 2024). In addition, current automated systems are regarded as not yet capable of fully autonomous decision-making, indicating continued demands on navigational and operational competence during WAPS operations (Fava & Satta, 2025; Wang et al., 2022).

Regardless of the level of automation, operation of WAPS, responsibility for ship handling, navigation, and operation remains with the master and crew (Chou et al., 2021; Nelissen et al., 2016; Wang et al., 2022). For instance, the crew should be able to respond to emergencies. This includes demands related to manual override of automated systems, management of equipment or component failures, emergency procedures and responses, heavy weather conditions, and other safety hazards associated with operation of WAPS (Argyros, 2015; Atkinson et al., 2018; EMSA, 2023; IMO, 2024; Lamvik et al., 2025). In addition, seafarers are required to recognize and assess new risk situations associated with WAPS operation (Fava & Satta, 2025).

3.3. *Competence Requirements in WAPS Operations*

Building on the operational and work-related demands described in section 3.2., the literature identifies competence requirements for safe and effective operations. In parallel, research on MET related to emerging and green technologies points to a need for strengthened competences, including technical and non-technical skills, technological familiarity, and sustainability awareness, as well as a need for improved critical thinking skills (Supangat & Malik, 2025; Wulandari et al., 2025).

3.3.1. *Technical and Operational Competence*

Across the records included, technical and operational competence requirements are focused on system-specific understanding of WAPS. This includes knowledge of system functionality, operation modes, and performance characteristics across varying environmental conditions (IMO, 2024; Lamvik et al., 2025; Rieffel et al., 2025). Operators' understanding of automated control systems and human-machine interaction is highlighted in relation to safe and effective operation (Rieffel et al., 2025).

Operational competence is further addressed in relation to vessel handling, navigation, and maneuverability (Atkinson et al., 2018). This includes competence related to sail handling, control adjustments, and the operational use and interpretation of performance-relevant information during operation (Wang et al., 2025). Further, it involves information related to energy efficiency and system performance, which is identified as operationally relevant for the effective use of WAPS (Lamvik et al., 2025; Xing et al., 2020).

In addition, technical competence related to maintenance, trouble shooting, and system monitoring is highlighted (Lamvik et al., 2025; Xing et al., 2020). The publications further describe the need for operators to manage both routine maintenance tasks and unexpected system malfunctions to support safe and efficient operations of WAPS (IMO, 2024; Xing et al., 2020).

3.3.2. *Non-Technical Competences*

Besides technical and operational competences, non-technical competences associated with the operation of vessels equipped with WAPS are highlighted. For instance, onboard decision-making and situation assessment are highlighted (Chou et al., 2021; Wang et al., 2022). Operators are required to continuously interpret multiple sources of information, balance competing operational objectives, and adjust decisions in response to dynamic operational conditions during WAPS operation (Fava & Satta, 2025; Lamvik et al., 2025).

Adaptability and flexibility are further emphasized as relevant competences, as WAPS introduce changes to established navigation and ship-handling practices. Seafarers are required to adapt existing procedures, manage new task demands, and respond to unfamiliar operational scenarios associated with the integration of WAPS technologies (Lamvik et al., 2025; Wang et al., 2022).

In addition, perceptions of risk and workload are discussed as relevant non-technical aspects of WAPS operation (Atkinson et al., 2018; Wang et al., 2022). Limited operational experience with WAPS contributes to uncertainty and perceived risk among operators and decision-makers (EMSA, 2023). At the system level, a lack of full-scale trials and empirical performance data creates hesitation and risk aversion toward WAPS (Rehmatulla et al., 2017). Complementing this, seafarer-focused studies emphasize how such uncertainty is experienced in practice, shaping workload, decision-making, and the need for adaptation during operation (Fava & Satta, 2025).

3.4. *Training and Learning*

The included literature describes a range of training and learning that aims to support safe and efficient operation of WAPS. These practices span formal and informal training approaches and experiential learning during operation embedded in existing regulatory and organizational frameworks.

3.4.1. *Training Approaches and Learning Modalities*

Training related to WAPS is described as largely based on a combination of manufacturer-provided documentation, onboard familiarization, and learning through operational experience. Initial training is often provided through system manuals and guidance developed by technology suppliers, with competence development occurring primarily during early deployment and operation of the systems (IMO, 2024; EMSA, 2023).

It is suggested that simulator-based and digital training approaches are regarded as increasingly relevant for WAPS and other emerging maritime technologies. Simulator training is discussed as a means to support understanding of system behavior, navigation-related scenarios and emergency situations under controlled conditions, particularly where full-scale practical training is limited (Rieffel et al., 2025).

Digital and e-learning formats are further described as enabling flexible and individual access to training content and supporting blended learning approaches (Bertram & Plowman, 2020). Beyond familiarization with specific systems, education and training are described as supporting competence development for emerging green technologies. In particular, simulator-based training and suitable curriculum may foster critical thinking, system understanding, and sustainability awareness competences among future seafarers (Supangat & Malik, 2025; Wulandari et al., 2025).

3.4.2. *Limitations of Existing Training and Learning Practices*

The literature identifies several limitations related to existing training, learning, and safety practices for WAPS and other emerging maritime technologies. Maritime education and training institutions (MET) face challenges in keeping pace with the rapid evolution of maritime technologies, with industry development often progressing faster than academic curricula. This results in a misalignment between competence development content and evolving industry demands, which is outlined as a recurring gap (Simanjuntak et al., 2025; Wulandari et al., 2025). A recurring theme concerns the fragmented and uneven development of training provision, which is often dependent on local initiatives, technology providers, or individual companies rather than standardized and widely accessible training frameworks (EMSA, 2023; Lamvik et al., 2025). In particular, METs are reported to offer limited formal training schemes specifically addressing WAPS operation (Lamvik et al., 2025). In addition, broader gaps in competence development related to emerging and green maritime technologies are identified across the literature (Supangat & Malik, 2025; Wulandari et al., 2025).

Several records further describe current training practices as largely shaped by compliance with existing international regulations and certification requirements (Rehmatulla et al., 2017; Wulandari et al., 2025). This contributes to variability in training content and scope across organizations and educational institutions.

Furthermore, limited involvement of seafarers' perspectives in the development of training and safety practices is identified as an additional limitation (Fava & Satta, 2025). Studies addressing operational experience emphasize that practical knowledge, situational judgment, and experiential learning play a central role in safe operations, yet these elements are not always systematically captured or reflected in formal training programs (Fava & Satta, 2025; Lamvik et al., 2025). Consequently, learning related to WAPS is often described as occurring during early operational phases rather than through structured preparation.

Finally, responsibility for training and learning is distributed across multiple actors, including technology providers, shipping companies, and METs. The distributed responsibility may contribute to gaps in training provision, particularly in cases where emerging technologies are still evolving and operational experience remains limited (IMO, 2024; Rojon & Dieperink, 2014).

3.5. *Safety Considerations and Risk-Oriented Practices*

Safety considerations related to WAPS are closely linked to situational conditions and operational decision-making. The literature highlights that safety in WAPS operations is managed through operational adjustments during everyday work, including the reduction of sail area, system disengagement, and modification of operational profiles in response to environmental and navigational conditions (EMSA, 2023; Gaul & Rutkowski, 2025).

In addition to operational practices, safety considerations for WAPS are shaped by vessel-specific and context-dependent demands as effects on ship handling, maneuverability, stability, visibility, and air draught, which are influencing both navigational safety and operational feasibility (Atkinson et al., 2018; EMSA, 2023).

At the system and approval level, safety for novel maritime technologies such as WAPS is often established through risk-based design approaches. Where existing prescriptive regulations do not explicitly address new technologies, alternative design and arrangement processes are used to identify hazards, assess risks, and demonstrate equivalent levels of safety (Argyros, 2015). These design-phase safety assessments are described as informing subsequent operational limitations and safety-related procedures.

Overall, the included literature describes safety considerations for WAPS as embedded in operational and organizational practice but primarily addressed through existing operational frameworks (Atkinson et al., 2018; EMSA, 2023).

4.Discussion

This review synthesizes evidence on institutional and regulatory context, operational demands, competence requirements, and current training and safety practices related to WAPS. Across these areas, the findings point to a mismatch between evolving operational demands and the lack of international standards for competence frameworks and training.

As outlined in 3.1, a gap within the regulatory framework becomes visible: Institutionally, the international regulatory framework that normally standardize training and competences is not yet developed for WAPS. This has already been recognized by the IMO, (2024), which signals emerging institutional efforts to address these gaps as the field matures. Taken together with Lamvik et al. (2025) as outlined in 3.5, industry may take responsibility for initiating competence development in areas of new technology as WAPS where standards are lacking. This engagement aims for risk-free operation of WAPS and is therefore closely related to the different operational demands introduced. As outlined in 3.2, WAPS create operational variability and new decision-making demands, due to more complex ship motions and maneuverability. Automation shifts demands, however, responsibility remains with the crew. Safe performance depends on monitoring, intervention, judgment, and adaptability. Taken together, these characteristics suggest that safe performance depends on real-time judgment and adaptive capacity under uncertainty.

In line with safe management of WAPS, this introduced complexity in demands is reflected in the competence requirements synthesized in 3.3 (e.g., system understanding, vessel handling, maintenance and troubleshooting). The results highlight non-technical competences related to situation assessment, decision-making, and procedural adaptation. However, even though these competences become a "safety barrier", they are not in line with today's safety management systems. Such are mainly based on prescriptive and standardized solutions, often materialized through excessive use of procedures where one size fits all, which is often referred to as *Safety-I* perspective. While WAPS introduces more complexity and uncertainty, this indicates that prescriptive solutions as used under this philosophy are limited in their application for WAPS. Therefore, competence can be regarded as bridging the gap between incomplete standards and the need for variable practice.

Based on that, it is necessary to assist seafarers in the development of those competences. However, training for WAPS is described in 3.4 as only fragmented provided and frequently experience-based. Onboard training often relies on manuals, onboarding, and learning during early operations. Current training is further following compliance-shaped practices and limited incorporation of seafarers' perspectives, even though safety, as visible in 3.5, is managed situationally through operational adjustments embedded in everyday work.

This can be summarized as follows: A lack of standards may contribute to insufficient competence development through training. However, incident-driven standardization, following a less suitable safety perspective, may be insufficient in supporting adaptational competences for new operational demands.

When interpreted in relation to prevailing existing maritime safety and competence frameworks, those findings suggest tensions between operational characteristics of WAPS and current safety management approaches. As mentioned earlier, those approaches primarily rely on predefined procedures and standardized learning, based upon an underlying, incident-based, risk-identifying philosophy, *Safety-I* (Hollnagel, 2014). Attempts to improve safe operation of a system through implementation of additional standards and guidelines as common in today's Safety Management (Li & Guldenmund, 2018) may limit the effectiveness of WAPS when operational conditions remain uncertain. Regulatory frameworks may hinder development of full potential of new technologies (Boring et al., 2022) and may also cause the precautionary principle to fail (Wiener, 2004), if WAPS is "pressed" into existing regulations. By doing so, it contradicts the aim of safety management, if knowledge development is less "wished", but "certificate-needed-designed", even if it can act as safe barrier itself (Li & Guldenmund, 2018).

Instead, through the lens of Newer Safety Paradigms (NSPs) such as *Safety-II* or *Safety Differently,* the findings can be understood as highlighting the central role of human adaptability, situational judgement, and operational flexibility in managing safety under conditions characterized by uncertainty and limited system maturity. Rather than viewing deviations from standardized procedures as failures, the results point to adaptive practices as integral to maintaining safe operations during early phases of WAPS adoption. NSPs represent a pro-active, more agile, performance-based learning approach in safety management (Hollnagel, 2014). In this perspective, acknowledging seafarers' expertise and competences is essential. Further, effective safety management should be created around seafarers' needs and practices, to deal with the complexities of WAPS (Adhita et al., 2023; Dekker, 2014).

To enhance safety management, strengthening competences as a safety barrier can be beneficial.

This is in line with Li & Guldenmund (2018) who emphasize competence and training as key safety barriers. Training for WAPS operations should therefore be designed to match the specific competencies required. It is important to equip seafarers with "practical wisdom" (Flyvbjerg, 2009), assisting them in getting competent and being able to experiment, reflect and construct their own model of WAPS system behavior and operational boundaries. As outlined in 3.2, the operational demands of WAPS differ greatly between its different types. Adaptation to WAPS and its requirements is a key competence and cannot be achieved through automation only or without additional knowledge. In this context, automation can be interpreted as a predefined safety layer that organizations effectively apply a *Safety-I* strategy to "patch" gaps in the current maritime framework. However, this constitutes practical confirmation that the framework itself has not been designed for operational variability and uncertainty introduced through new technologies such as WAPS.

When automation cannot replace human adaptiveness, safe operation must be achieved by strengthening human adaptive capacity as emphasized by NSPs. While multiple training methods are available, resilience is best strengthened through approaches that enable human interaction, guided practice, and reflection. Learning formats with less interaction (e.g. online courses) are therefore of limited value, which calls for closer collaboration between METs and industry.

Consequently, to enhance human adaptability and resilience, training should focus on system awareness, operational parameters, safety, and system integration (IMO, 2024). Furthermore, future research should involve the seafarer's perspective since their viewpoints are regarded as essential, representing the link between onboard-operations and shore-based decision-makers (Fava & Satta, 2025).

In summary, successful integration of WAPS requires a paradigm shift from rule-based compliance to more adaptational approaches, supported by training methods and different standards.

5.Conclusion

This review examines the operational and human dimensions of WAPS. It indicates that current regulatory approaches may be insufficient in managing operational complexity and novelty of WAPS and associated challenges. As a result, safe and efficient integration depends not only on technical performance but on how socio-technical work systems support adaptive decision-making and learning in everyday operations.

Training emerges as an effective safety barrier, fostering critical thinking and system awareness. Therefore, blended learning with different methodological approaches is essential.

The reviewed literature indicates that further research within operational and human dimensions is needed. Therefore, future research should focus on ethnographic studies on current adaptation from seafarers on vessels with WAPS to further understand the operational and human dimensions in onboard life. Further, the practical application of NSPs could be tested in the real-world setting. However, therefore it will require close collaboration between METs institutions and industry.

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