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Training and Competency Gaps for Shipping Decarbonization in the Era of Disruptive Technology: The Case of Panama

Javier Eloy Diaz Jimenez [1,*], Eddie Blanco-Davis [2], Rosa Mary de la Campa Portela [3], Sean Loughney [2], Jin Wang [2] and Ervin Vargas Wilson [1]

1 Facultad de Ciencias Náuticas (FACINA), Universidad Marítima Internacional de Panamá (UMIP), La Boca, Edificio 1033, Ancón, Panama City 0843-03092, Panama; evargas@umip.ac.pa
2 Liverpool Logistics, Offshore and Marine Research Institute (LOOM), Liverpool John Moores University (LJMU), Liverpool L3 3AF, UK; e.e.blancodavis@ljmu.ac.uk (E.B.-D.); s.loughney@ljmu.ac.uk (S.L.); j.wang@ljmu.ac.uk (J.W.)
3 Escuela Técnica Superior de Náutica y Máquinas (ETSNM), Universidade da Coruña (UDC), Plaza Marina Mercante, 15011 A Coruña, Spain; rosa.mary.campa@udc.es
* Correspondence: jdiaz@umip.ac.pa

Abstract

The maritime sector is undergoing a profound transformation driven by disruptive technologies and global decarbonization objectives, placing new demands on Maritime Education and Training (MET) systems. Equipping maritime professionals with competencies for low-carbon shipping is now as critical as technological advancement itself. This study examines how disruptive technologies can be effectively integrated into MET frameworks to support environmental sustainability, using Panama as a representative case study of a major flag and maritime service state. A mixed-methods approach was adopted, combining a structured literature review, expert surveys, and a multi-criteria decision-making analysis based on the Analytic Hierarchy Process (AHP). The findings reveal a significant misalignment between existing MET curricula and the competencies required for decarbonized maritime operations. Key gaps include limited training in alternative fuels, emissions measurement and reporting, energy-efficient technologies, digital analytics, and regulatory compliance. Stakeholders also reported fragmented training provision, uneven access to emerging technologies, and weak coordination between academia, industry, and regulators, particularly in developing contexts. The results highlight the urgent need for curriculum reform and stronger cross-sector collaboration to align MET with evolving technological and regulatory demands. The study provides an applied, evidence-based framework for MET reform, with insights transferable to other systems facing similar decarbonization challenges.

Keywords: alternative fuels; decarbonization; maritime education and training; sustainable shipping

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1. Introduction

The maritime industry, which facilitates approximately 90% of global trade, is undergoing a significant revolution in response to the dual imperatives of climate change mitigation and the integration of disruptive technologies [1,2]. These shifts are not only redefining ship design and operations but are also fundamentally reshaping the professional competencies required of seafarers and maritime professionals [3,4]. Central to this transformation is shipping decarbonization, a critical pathway for reducing global greenhouse gas (GHG) emissions [3]. In July 2023, the International Maritime Organization (IMO) adopted a revised GHG Strategy, setting an enhanced ambition to achieve net-zero GHG emissions from international shipping by or around 2050, while considering different national circumstances [5]. Achieving these targets extends beyond technological and regulatory change and requires a systematic transformation of the maritime workforce through education and training systems capable of developing competencies aligned with emerging technologies, evolving regulatory frameworks, and environmental performance requirements [3,4].

MET frameworks are essential for preparing seafarers to meet the technological and environmental demands of a rapidly evolving maritime industry [6,7]. Traditionally, MET has focused on developing the technical and operational competencies necessary for safe and efficient maritime operations [8,9]. However, the imperatives of decarbonization and the integration of disruptive technologies necessitate a paradigm shift in MET curricula [10]. In response, the International Maritime Organization (IMO) has initiated a comprehensive review of the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW Convention) to address emerging competency requirements. This review encompasses 22 specific areas, notably emphasizing the incorporation of twenty-first-century skills such as digital literacy, effective communication, information management, and adaptability to changing work environments [11,12]. These competencies are increasingly critical for effective engagement with alternative fuels, emissions management systems, energy-efficient technologies, and digital transformation tools central to decarbonization efforts [7,13]. Aligning MET frameworks with these evolving requirements introduces systemic challenges for MET institutions, including the need for substantial curriculum reform, faculty upskilling, and infrastructure investment to accommodate emerging technologies such as digital twins and autonomous systems [14,15]. Overall, the multifaceted nature of decarbonization, encompassing technical, operational, and regulatory dimensions, demands a multidisciplinary and multisectoral approach to training that extends beyond traditional seamanship skills [12,16].

This study prioritizes and designs a future-ready MET framework for Panama by assessing the sector's readiness for the decarbonization transition, identifying key competency gaps, and evaluating the effectiveness of existing training programs. This emphasis is especially critical for Panama, whose strategic role as a global maritime hub through the Panama Canal positions it as a key player in the implementation of international decarbonization initiatives [17]. Furthermore, Panama operates one of the largest ship registries in the world, representing over 16% of the global fleet by tonnage [2], which reinforces its global maritime responsibility and highlights the strategic importance of a robust MET framework capable of aligning national capabilities with international environmental and operational standards. While the empirical focus is national, the analytical approach, opportunities, and challenges identified are representative of those faced by other maritime administrations, flag states and MET contexts navigating similar decarbonization and technological transitions.

Accordingly, to address these objectives, the study is guided by the following Research Questions:

- What are the key challenges and opportunities for integrating sustainability principles, emerging technologies, and the transition to alternative fuels into MET curricula in Panama?
- How can international regulatory frameworks and industry collaborations support this integration into MET systems to ensure alignment with global maritime sustainability goals?
- What are the current competency gaps in the Panamanian maritime context related to decarbonization and emerging technologies transition?

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- How can the findings be synthesized to propose a comprehensive, context-specific MET framework for Panama that effectively aligns workforce training with emerging technologies, regulatory requirements, and global sustainability goals?

These questions highlight the need to bridge traditional MET with the upskilling and reskilling required for a low-carbon, technology-driven maritime sector. The findings provide strategic guidance for policymakers, MET institutions, and industry stakeholders to align training with global decarbonization goals, strengthening Panama's position as a regional leader in sustainable and future-ready MET. To address these research questions, a mixed-methods approach integrating quantitative and qualitative techniques was employed. This methodology included an extensive literature review, structured surveys with maritime professionals, focus group discussions, and the Analytic Hierarchy Process (AHP), a widely recognized Multi-Criteria Decision-Making (MCDM) tool for prioritizing complex, multi-dimensional challenges [18,19]. AHP was selected for its ability to decompose complex decision problems into a hierarchical structure, enabling precise pairwise comparisons and deriving priority weights based on expert judgments [20,21]. This approach is particularly well-suited for the prioritization of competencies required for maritime decarbonization, focusing on a context-specific MET framework for Panama. While other MCDM methods, such as TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [22], VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) [23], Bayesian Networks [24], and DEMATEL (Decision Making Trial and Evaluation Laboratory) [25] have been effectively applied in the maritime sector for risk assessment, technology selection, and operational strategy evaluation, AHP was chosen for its proven reliability in competency prioritization, clear interpretability, and robust handling of subjective expert input [26]. This methodological approach integrates the practical insights of maritime professionals, providing a structured yet flexible framework to address the multifaceted challenges of maritime decarbonization [27].

The remainder of this paper is structured as follows: Section 2 (Literature Review) provides a comprehensive analysis of existing research on MET for decarbonization, including key competency gaps. Section 3 (Methodology) describes the data collection and analysis techniques employed, including the AHP for prioritizing critical competencies within the Panamanian maritime sector. Section 4 (Preliminary Results) presents findings on current training gaps, institutional readiness, and alignment with decarbonization goals, derived from structured surveys and expert insights. Finally, Section 5 (Conclusions and potential policy implications) outlines the strategic importance of a country-specific MET framework in supporting decarbonization, enhancing workforce capabilities, and positioning Panama as a regional hub of capacity building. Collectively, the study positions MET as a paramount enabler of the technological and regulatory transition required to achieve a sustainable and low-carbon shipping sector.

2. Literature Review

2.1. MET in the Era of Transformation

The transformation of MET to meet the challenges of decarbonization, digitalization, and sustainability has emerged as a global priority [28]. As maritime industries evolve under pressure from international climate goals and technological change, MET systems are expected to deliver future-ready, interdisciplinary education and training [3].

This transformation is also associated, in the literature, with broader institutional and pedagogical implications, including curriculum restructuring, the adoption of experiential and simulation-based learning, faculty upskilling, and closer alignment between educational institutions, industry stakeholders, and regulatory authorities [6,10,29]. The urgency of this transition is further reflected in DNV's Future of Seafarers 2030 report, which indi-

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cates that over 75% of seafarers will require training in alternative fuels, while 81% will need advanced digital skills [7]. Studies consistently emphasize the need for seafarers to acquire both technical and non-technical competencies to operate in increasingly complex environments [6,10,29]. The urgency of this transformation is further reflected in DNV's Future of Seafarers 2030 Report, which indicates that over 75% of seafarers will require training on alternative fuels, while 81% will need advanced digital skills [7].

2.2. Decision-Support Tools in MET: The Role of AHP and MCDM

Within this context, decision-support tools such as Multi-Criteria Decision-Making (MCDM) methodologies, particularly the Analytic Hierarchy Process (AHP) [21], have proven essential for evaluating training needs, prioritizing competencies, and supporting policy alignment. Several studies have applied AHP within competency-based training frameworks; for example, ref. [30] employed AHP to design marine engineering training grounded in expert judgment, while [31] analyzed training typologies from a learner-centric perspective.

AHP has also been applied to emerging technological domains, with [32] prioritizing competencies for remote operators of Maritime Autonomous Surface Ships (MASS), demonstrating its adaptability to novel operational contexts. Other studies have highlighted AHP's capacity to balance competing technological, regulatory, and educational priorities in MET design [26,33].

Hybrid and extended MCDM approaches have further expanded this analytical landscape. For instance, ref. [34] applied a SWOT–AHP framework to biodiesel adoption, while methods such as the Bayesian Best-Worst Method, Fuzzy AHP, and Delphi–AHP have been used in simulator evaluation [35], maritime cybersecurity education [36], sustainability and ocean literacy initiatives [37], and the development of "green curriculum" frameworks [38]. Collectively, these studies demonstrate AHP's versatility in addressing maritime competency gaps; however, existing research remains largely concentrated in developed maritime regions, leaving notable gaps in Latin America.

2.3. Regulatory Imperatives and Global Alignment

At the regulatory level, Lloyd's Register [3] and the IMO's Sub-Committee on Human Element, Training and Watchkeeping underscore the urgent need to revise MET to ensure safety and sustainability in line with 2023 IMO GHG Strategy. A key development is the IMO's comprehensive revision of the STCW Convention [11] which explicitly targets competencies related to alternative fuels, emissions monitoring, and digital technologies that were not prioritized in earlier frameworks. This regulatory momentum creates both opportunities and challenges for national MET systems, particularly in aligning curricula with global standards. Existing literature indicates that the translation of international regulatory frameworks into national MET systems is often constrained by challenges related to curriculum adaptation, institutional capacity, faculty preparedness, infrastructure investment, and regulatory coordination across governance levels.

2.4. The Regional Gap: Panama and Latin America

Despite Panama's minimal national GHG footprint, its status as a carbon-negative nation with 65.4% forest cover [39], and the country's central role in global maritime trade, exemplified by the CO_2 emissions associated with the approximately 13,000 Canal transits per year [40], highlight the urgent need for a resilient, context-specific MET framework. However, existing literature offers limited insight into how national MET systems in major flag and transit states like Panama can strategically align with global decarbonization goals.

This study addresses this critical gap by prioritizing competencies and assessing the readiness of Panama's MET framework through a structured, evidence-based approach.

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In doing so, it contributes to a regionally grounded, policy-relevant model for advancing maritime decarbonization capacity in strategic global hubs.

Yet, literature addressing how flag states and transit hubs like Panama can strategically align MET with global decarbonization and digitalization goals remains scarce. Existing research often highlights global challenges without accounting for regional disparities in training capacity, infrastructure, or regulatory alignment.

Furthermore, this study directly addresses these identified gaps by developing a structured, evidence-based framework to prioritize the competencies most critical for Panama's maritime decarbonization strategy. By applying the AHP to assess the readiness of Panama's MET system, the research integrates expert judgments to generate robust, context-specific insights. Unlike existing studies that often examine decarbonization and digital transformation in isolation, this study combines both dimensions within a single analytical framework, thereby reflecting the intertwined nature of technological, regulatory, and environmental transitions.

The result is a policy-relevant model that not only advances the global discourse on MET reform but also provides a regionally grounded approach tailored to Panama. Accordingly, Panama's role as one of the world's largest flag states and a strategic maritime hub positions this contribution as a potential reference point for other developing maritime economies seeking to align national training systems with global decarbonization imperatives.

3. Methodology

This study employed a sequential mixed-method design. First, an exploratory expert survey (see Appendix A) was conducted to identify and refine key criteria. Second, the AHP was applied to systematically prioritize these criteria, integrating qualitative expert judgment with quantitative rigor. To support the prioritization process and ensure the contextual validity of the AHP framework, an initial structured expert survey was administered to a purposive sample of 25 experienced professionals from Panama's maritime sector. The survey captured expert assessments of key themes related to MET for shipping decarbonization, drawing on participants' operational, technical, regulatory, and academic expertise. Survey responses were synthesized through thematic aggregation and comparative assessment, allowing recurrent and conceptually aligned themes to be consolidated into five main criteria. These criteria were iteratively refined, through 23 targeted questions, to ensure conceptual clarity, internal consistency, and relevance prior to their formal prioritization using AHP.

As summarized in Table 1, this process ensured a transparent linkage between survey inputs and the final model architecture, while avoiding arbitrary criterion selection.

Although the sample size may appear modest, a purposive sampling approach was deliberately applied to ensure the inclusion of experts with direct operational, regulatory, academic, and technical experience relevant to MET and shipping decarbonization. This approach aligns with established methodological practices in AHP and expert-based decision analysis, where analytical validity depends on the depth, relevance, and expertise of respondents rather than on statistical representativeness. Similar expert-panel sizes have been adopted in recent peer-reviewed studies addressing energy transitions and maritime governance, confirming the methodological adequacy of this approach [41,42].

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Table 1. Structured expert survey.

No.	Main AHP Criteria	Survey-Derived Aggregated Inputs	Conceptual Focus
F1	Workforce Competence Development	Expert assessments of training adequacy, digital skill requirements, and emerging technical and non-technical competencies (Question: 13, 14, 15, 16, and 17)	Training models, Digitalization, Technical and transversal skills
F2	Policy Regulatory Support	Expert evaluations of awareness, alignment, and institutional readiness regarding IMO decarbonization goals and national policy frameworks (Question: 11, 19, and 23)	IMO Strategy, regulatory alignment, governance
F3	Industry Stakeholder Engagement	Expert perceptions of collaboration, mentorship, and cross-sectoral cooperation between industry, academia, and regulators (Question: 10 and 23)	Curriculum relevance, industry–academia collaboration
F4	Barriers to Effective Implementation	Expert identification of structural, financial and organizational constraints affecting MET implementation (Question: 19 and 20)	Training costs, infrastructure, instructor readiness
F5	Environmental and Sustainability Literacy	Expert insights on sustainability integration, interdisciplinary learning, and inclusion of climate-related competencies (Question: 20 and 23)	SDGs, climate literacy, curriculum modernization

Source: Author.

Accordingly, the inclusion of 25 qualified participants ensured analytical robustness and reliable pairwise comparisons. The final configuration of sub-criteria reflects the consolidation of recurrent and conceptually aligned expert judgments, retaining those dimensions that demonstrated both relevance and internal consistency within the decision model, thereby reinforcing the contextual legitimacy of the prioritization outcomes for Panama's maritime education and decarbonization framework.

Furthermore, based on the results of the initial survey, the prioritization AHP model was later employed to evaluate the relative importance of criteria shaping a future-ready MET framework for Panama's shipping decarbonization strategy by organizing decision elements hierarchically, the overall goal at the top, main criteria [F1], [F2], [F3], [F4] and [F5] at the second level, and sub-criteria beneath each criterion [F11], [F12], [F13], [F14], [F21], [F22], [F31], [F32], [F41], [F42], [F43], [F44], [F51] and [F52], as shown in Figure 1. In accordance, to further strengthen the foundation of the model used, a targeted group of thirty (30) maritime academics, lecturers, instructors, and professors from across Panama were selected to complete the prioritization AHP model survey instrument, a sample size aligned with recommended thresholds for group decision-making in AHP studies [18,19]. These individuals were identified as primary stakeholders due to their direct involvement in MET within the country. Their expert judgments provided the primary source of input for the AHP model, ensuring that the derived priorities reflect both academic expertise and the operational realities of the Panamanian MET ecosystem.

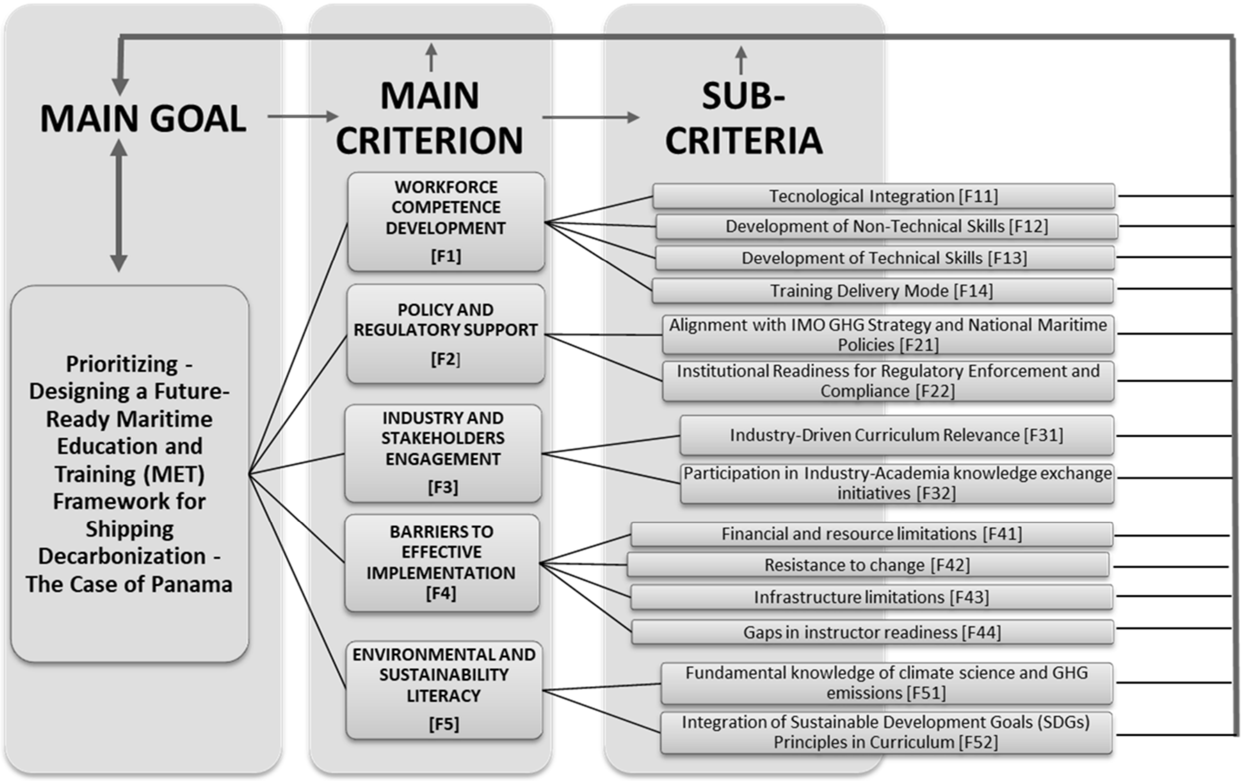

Figure 1. Hierarchical structure for MET Framework. Source: Author.

Figure 1 illustrates the hierarchical structure guiding the AHP model in this study, which decomposes the decision problem, prioritizing and designing a future-ready MET framework for Panama, into three (3) levels: the goal, five main criteria, and related sub-criteria. This structure supports systematic pairwise comparisons, with expert judgments applied using Saaty's scale of relative importance [21], ranging from 1 (equal importance) to 9 (extreme importance), with reciprocal values (e.g., 1/3, 1/5) representing less importance in the opposite direction [18], as shown in Table 2. The comparison results are processed through a pairwise comparison matrix that generates normalized priority weights for each criterion and sub-criterion, capturing both quantitative and qualitative assessments of relevance [19,20].

Table 2. Saaty's Fundamental Scale for Pairwise Comparisons.

Intensity of Importance	Definition	Reciprocal Value—Intensity of Unimportance	Definition
1	Equally important	1	Equally important
3	A little important	1/3	A little unimportant
5	Important	1/5	Unimportant
7	Very important	1/7	Very unimportant
9	Extremely important	1/9	Extremely unimportant
2, 4, 6, 8	Intermediate important values	1/2, 1/4, etc.	Intermediate unimportant values

Source: Data adapted from [20,21].

The hierarchical breakdown ensures analytical transparency and methodological robustness by allowing decision-makers to isolate and evaluate individual components of the MET framework. Furthermore, this structure enhances the reliability and consistency of expert input, forming the basis for the calculation of consistency ratios and eigenvalues to validate the prioritization logic. By integrating this structured model within the AHP framework, the study ensures that the prioritization of training competencies and policy interventions is grounded in a systematic, replicable, and stakeholder-informed process [18,21].

Building on this methodological foundation, the next step involved translating expert judgments into a structured comparison framework. Thus, the relative importance of criteria was elicited through pairwise comparisons provided by the selected experts, enabling the construction of a consistent matrix representation of their evaluations, where *aij* represents the relative importance of criterion "*i*" over criterion "*j*" as assigned by 30 experts. A complete pairwise comparison *matrix A* of size n × n is formed using the 5 main criteria addressed [F1], [F2], [F3], [F4] and [F5], as shown in Formula (1):

$$A = \begin{bmatrix} 1 & F1/F2 & F1/F3 & F1/F4 & F1/F5 \\ F2/F1 & 1 & F2/F3 & F2/F4 & F2/F5 \\ F3/F1 & F3/F2 & 1 & F3/F4 & F3/F5 \\ F4/F1 & F4/F2 & F4/F2 & 1 & F4/F5 \\ F5/F1 & F5/F2 & F5/F3 & F5/F4 & 1 \end{bmatrix} \quad (1)$$

The vector w = [w1, w2,. . .,wn]^T represents the Priority Vector obtained after the normalization process of the pairwise comparison matrix. Each component "w*i*" corresponds to the relative weight assigned to a given criterion, thereby reflecting its importance in the overall decision-making framework. Normalization ensured that all weights are scaled proportionally so that they are directly comparable and collectively sum to one. In other words, this transformation converts raw judgments into a consistent set of dimensionless values that express the contribution of each criterion to the final evaluation. An approximation of the calculation process is provided in Formula (2), which illustrates how these weights are derived through normalization procedures applied to the pairwise comparison matrix using the 5 main criteria [F1], [F2], [F3], [F4] and [F5].

$$\boldsymbol{w_k} = \frac{1}{5}\sum_{j=1}^{5}\left(\frac{a_{kj}}{\sum_{i=1}^{5} a_{ij}}\right)\ (k = 1,\ 2,\ 3,\ 4,\ 5) \quad (2)$$

To ensure the reliability of the judgments provided by the 30 experts, it was essential to evaluate the internal consistency of the pairwise comparisons. This was achieved through the Consistency Ratio (CR), which measures whether the judgments are logically coherent or if they contain excessive contradictions. The first step in this process involves calculating the Consistency Index (CI), which requires determining the maximum eigenvalue (λmax) of the comparison matrix. The expression for max, as shown in Formula (3), is obtained by combining the weighted sum vector with the normalized priority vector w.

$$\boldsymbol{\lambda_{max}} = \frac{1}{5}\sum_{j=1}^{5}\left(\frac{\sum_{k=1}^{5} w_k a_{jk}}{w_j}\right) \quad (3)$$

Once λmax was obtained, the CI was computed according to Formula (4):

$$\boldsymbol{CI} = \frac{\lambda_{max} - 5}{4} \quad (4)$$

Here, the denominator represents the number of criteria minus one (n − 1). A CI value close to zero indicates that the judgments are highly consistent, whereas larger values suggest the presence of inconsistencies that may undermine the reliability of the decision-making process. While the CI provided a numerical measure of coherence within the judgments of the 30 experts, it did not, by itself, determine whether this level of consistency was acceptable. To evaluate the adequacy of the CI, we benchmarked it against a reference

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value that reflected the likelihood of random judgments. This comparison was made through the CR, as expressed in Formula (5):

$$\boldsymbol{CR} = CI/RI \tag{5}$$

In this formulation, the CI was standardized by dividing it by the Random Index (RI), a value empirically derived from simulations of randomly generated pairwise comparison matrices of the same order. The RI varied according to the size of the matrix, as illustrated in Table 3. A CR value below 0.10 is considered acceptable, indicating that the pairwise comparisons demonstrated logical consistency. Conversely, when the CR exceeded this threshold, expert judgments were subject to further review or adjustment. In this way, the CR offered a normalized and objective measure that enabled us to confirm that the consistency observed in expert evaluations fell within an acceptable and methodologically sound range. The CR in the proposed matrix were below the 0.10 threshold, confirming the internal consistency of stakeholder inputs used in this full-scale application.

Table 3. Saaty's Random Index (RI) Values.

Order of Matrix (n)	2	3	4	5	6	7	8	9	10
RI Value	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Data adapted from [21].

In summary, the methodological framework applied in this study combines the hierarchical structuring of criteria, expert-driven pairwise comparisons, and rigorous consistency verification through the CI and CR, not as a mechanical step, but as a quality control mechanism ensuring the trustworthiness of the model outputs. This integrated approach ensures that the derived priority weights are not just mathematically sound but also grounded in the informed judgments of subject-matter experts directly engaged in MET in Panama. Thus, the methodological framework ensures internal transparency, replicability, and validity and also enhances the external relevance of the findings, providing decision-makers with a robust evidence base to guide MET strategies for shipping decarbonization.

4. Results

The analysis of the structured survey and subsequent application of the AHP framework generated results that offer a comprehensive picture of the current state of MET in Panama within the context of shipping decarbonization. The findings reflect not only the perceptions of 25 maritime professionals actively engaged in seafaring, training, regulation, and industry operations, but also the validation of these insights through the prioritized judgments of 30 academics and instructors directly involved in MET. Moreover, the results highlight critical competency gaps, institutional challenges, and opportunities for alignment with international sustainability mandates. Beyond identifying deficiencies, the outcomes also point toward concrete pathways for strengthening training programs, enhancing digital readiness, and fostering closer collaboration between the academia, industry, and regulatory bodies. In this way, the results provide both a diagnostic snapshot of the sector's current readiness and a roadmap for shaping a future-ready MET framework capable of supporting Panama's role in the global transition toward low- and zero-carbon shipping.

Furthermore, the findings reveal a strong consensus on the urgent need to integrate decarbonization competencies within MET frameworks. The prominence of Workforce Competence Development (F1) as the highest-ranked factor (40%), reflected in Figure 2, underscores a structural imbalance between current training provisions and the evolving technical demands of low- and zero-carbon operations. This outcome signals that the decarbonization transition in shipping is being constrained less by technological availability and more by a deficit in specialized human capital. In pedagogical terms, this finding highlights the need for curriculum redesigns that embed alternative fuel management, life-cycle emissions assessment, and digitalized vessel performance monitoring within both officer-level and engineering programs.

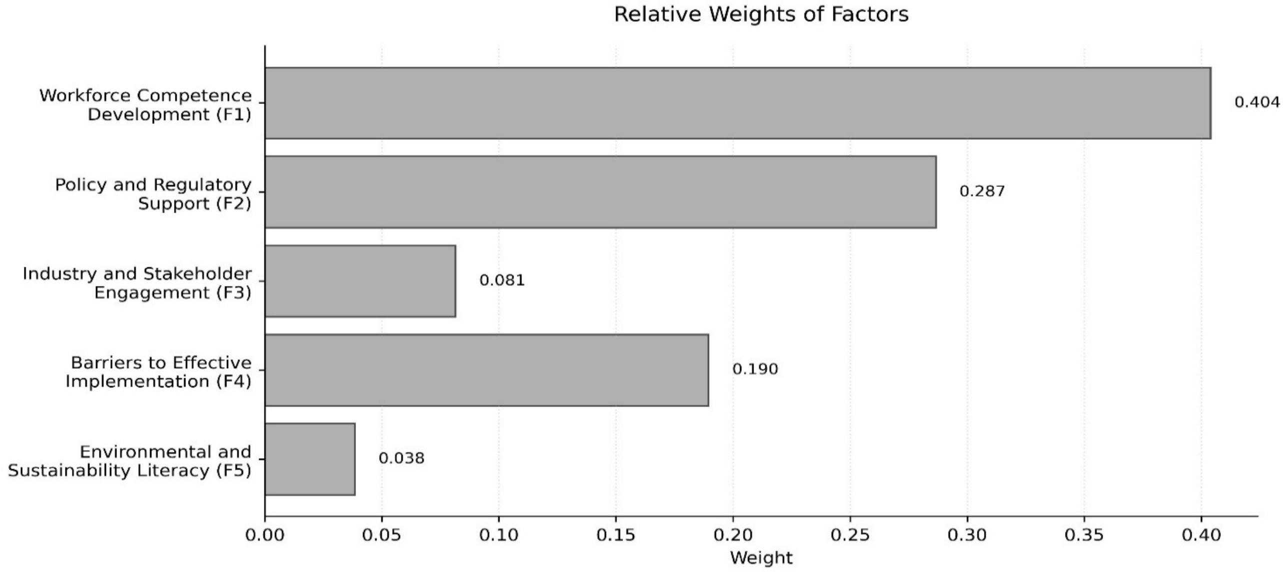

Figure 2. Initial AHP Simulation Results: Main Criteria Prioritization. Source: Author.

Collectively, these results imply that structural reform in MET must prioritize systemic linkages among regulation, workforce competence, and institutional capability. Such integration can be operationalized through multi-stakeholder partnerships, regional centers of excellence for maritime decarbonization training, and targeted funding schemes for simulator-based or dual-fuel technology instruction. In this sense, the factor prioritization not only quantifies the perceived importance of competence development but also delineates a roadmap for bridging the skills-policy gap that supports the broader energy transition in maritime transport.

The findings of this study reaffirm that MET reform is a strategic enabler of the maritime sector's decarbonization. The AHP prioritization results highlight regulatory alignment, technological competence, and institutional collaboration as the most critical drivers for building capacity toward low-carbon operations. These outcomes align with global transition frameworks, particularly the IMO Just Transition principles and Green Corridor initiatives, underscoring that MET modernization must be integrated with national maritime climate strategies and port decarbonization programs. Strengthening regional training alliances and harmonizing competency standards will be vital to support workforce readiness for alternative fuels, digital monitoring, and sustainable port operations. In essence, MET transformation is not only an educational priority but a structural pillar for achieving systemic maritime decarbonization.

As illustrated in Figure 2, Workforce Competence Development [F1] emerged as the most critical criterion, carrying a global weight of 40.4%, thus underscoring the centrality of human capital in enabling effective decarbonization within MET. This result highlights that without deliberate education reform and sustained investments in reskilling and upskilling, the sector risks lagging the technological, digital, and environmental transformations currently reshaping global shipping. Strengthening workforce competence, therefore, is a strategic imperative to ensure that seafarers and maritime professionals possess the adaptive skills needed to operate alternative fuel systems, manage emissions-reduction technologies, and comply with rapidly evolving international regulations. This was followed by Policy and Regulatory Support [F2] with 28.7%, reflecting the need for coherent regulatory frameworks and alignment with international standards, and Barriers to Effective Implementation [F4] at 19%, highlighting persistent structural, financial and operational challenges. Comparatively lower, yet still relevant, were Industry and Stakeholder Engagement [F3] at 8.1%, and Environmental and Sustainability Literacy [F5] with 3.8%, suggesting that while recognized, these areas have yet to consolidate into top-tier institutional priorities.

Turning to the sub-criteria results in Figure 3, Technological Integration [F11] accounted for 53.9% of F1's weight, making it the single most decisive sub-dimension of competency development. Similarly, Alignment with the IMO GHG Strategy [F21] dominated within F2 with 80.3%, confirming the pivotal role of global decarbonization mandates in shaping local policy action. Within F3, Industry-driven Curriculum Relevance [F31] represented 62.9%, signaling a clear demand for closer academia–industry linkages. Additional weight was distributed across implementation barriers, with Financial and Resource Limitations [F41] (50.8%) and Infrastructure Limitations [F43] (29.7%) being particularly salient. All sub-criteria weights were normalized in accordance with standard AHP procedures, and consistency was verified at this level prior to interpretation. Collectively, these findings reinforce that technological modernization, regulatory alignment, and curriculum–industry integration form the backbone of a future-ready MET system.

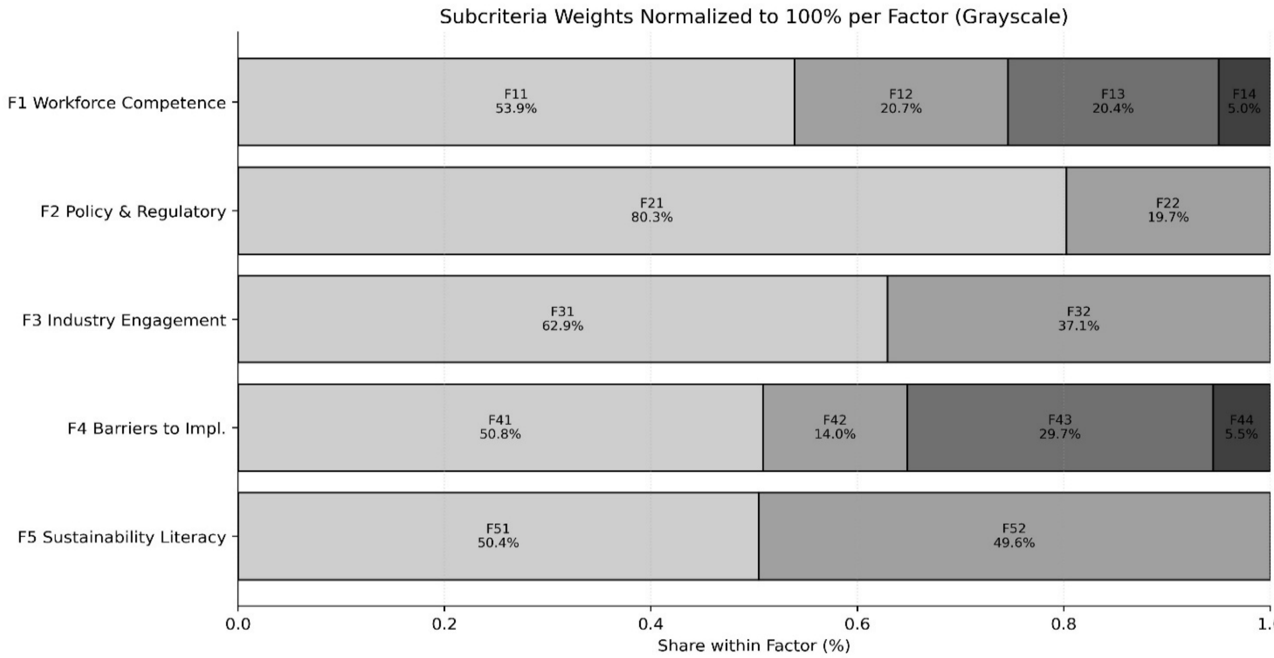

Figure 3. Weights of Sub-criteria. Source: Author.

In summary, the results underscore the urgency and strategic relevance of advancing decarbonization-oriented competencies within Panama's MET ecosystem. The convergence of expert perspectives reveals consistent concerns regarding training adequacy, institutional coordination, and digital readiness, alongside strong consensus on the importance of aligning national training agendas with global regulatory frameworks such as the revised 2023 IMO GHG Strategy. These findings validate the analytical approach employed and establish a robust evidence base for the subsequent discussion, where policy, institutional, and educational implications are examined in greater depth.

5. Conclusions and Potential Policy Implications

This study has addressed a critical gap in the literature and in practice by proposing and validating a context-specific MET framework for Panama that integrates sustainability, digital transformation, and the decarbonization agenda. At a time when the IMO is restructuring the STCW Convention to incorporate competencies previously absent from maritime training standards, the findings offer timely insights into how one of the world's largest flag states can anticipate and respond to these global developments.

First, the results highlight that the integration of sustainability principles and emerging technologies into MET curricula presents both challenges and opportunities. On the one hand, persistent gaps in technical infrastructure, institutional coordination, and faculty preparedness create significant barriers. On the other hand, Panama's scale and influence as a flag state position it to drive innovation, mobilize investment in training technologies, and act as a catalyst for regional knowledge transfer on the transition to alternative fuels and emissions reduction practices.

Second, the study underscores the importance of international regulatory frameworks and industry collaborations in supporting MET reform. The prioritization of regulatory alignment in the AHP model confirms that global instruments, such as the 2023 IMO GHG Strategy, regional sustainability commitments, and cross-sector partnerships, must play a central role in shaping curricula, ensuring that training institutions remain synchronized with evolving global standards and best practices. From a socio-technical systems perspective, this finding suggests that effective MET reform requires simultaneous adaptation of institutional structures, technologies, and human competencies within an interdependent ecosystem. Likewise, drawing on capability theory, the results highlight that regulatory coherence enhances not only institutional compliance but also the collective capacity of educators, seafarers, and policymakers to act within a low-carbon transition context. This integrative approach reinforces the strategic value of Panama fostering alliances with industry actors and regional partners to enhance interoperability, share resources, and accelerate digital and green skills development, positioning MET as a driver of systemic transition rather than a reactive training function.

Third, the analysis identified competency gaps in the Panamanian maritime context, particularly in areas related to the operation of alternative fuels, emissions monitoring, and the use of digital training technologies. The relatively low weight assigned to environmental literacy compared to workforce competence development signals an urgent need to reskill and upskill maritime professionals to ensure readiness for decarbonized operations. These gaps reflect a lack of curricular content and the limited diffusion of simulation-based and digital learning tools within training institutions. By addressing these gaps, the framework proposed here contributes to national and regional capacity building and positions Panama as a strategic knowledge hub capable of informing global standards in maritime decarbonization and digital readiness. The implications are both national and regional. For Panama, the adoption of this framework offers a pathway to strengthen its maritime human capital, modernize its training institutions, and reinforce its position as a regional reference point of maritime innovation and sustainability.

Finally, the synthesis of findings proposes a replicable conceptual approach for integrating decarbonization and digital transformation into context-specific MET framework for Panama, anchored in five main criteria: workforce competence development, policy and regulatory support, industry engagement, barriers to implementation, and environmental literacy. This framework emphasizes the need for continuous curriculum reform, systematic incorporation of digital and sustainable competencies, and robust mechanisms for stakeholder engagement. By doing so, it directly aligns workforce training with emerging technologies, regulatory imperatives, and global sustainability goals. In broader terms,

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the implications of this study extend beyond Panama. As a leading flag state, Panama's proactive adoption of a forward-looking MET framework can generate regional spillover effects, positioning Latin America as an active contributor to the maritime decarbonization transition. By bridging regulatory requirements, technological innovation, and human capital development, this framework strengthens national capacity and reinforces the region's relevance in the global maritime governance landscape. Future research could further refine the interpretation of AHP-based prioritization by incorporating additional analytical layers, such as explicit assessment of expert consensus, dispersion across sub-criteria, or sensitivity analyses within each main factor.

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Appendix A. Link to Access the Survey Conducted to 25 Experienced Professionals from Panama's Maritime Sector

https://drive.google.com/file/d/1CCqGnclru41PGFaetP3isVVM4-Z73an6/view?usp=sharing (accessed on 31 July 2025)

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