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TRANSPORT, 1

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Editorial Note

Transport 1 is the first special issue of the GeoProgress Journal on the various and multiple themes of transport, a field of studies that is truly important and central to a journal, like this, that is primarily concerned with development problems from the global to the local scale.

The papers proposed for publication in this Special have obviously been subjected to the same evaluation process as those proposed for the ordinary issues and approved according to the same rules and, in addition, on the basis of their thematic coherence.

We are grateful that the AGeI (Association of Italian Geographers) Group has proposed to this Journal the publication of the results of research of its members and its meetings and we can only hope that they will develop their research and put forward new proposals. We also hope that other study groups of the same AGeI and, no less, of other associations and disciplinary sectors, will entrust us with the editing and publication of the results of their scientific works.

For the specific contents of this issue, we refer to the Introduction, by Giuseppe Borruso.

Introduction

The Trieste Conference 2023

This special issue, dedicated to the broad and articulated theme of transport from a geographical perspective, brings together some contributions from colleagues with interests in transport and logistics within the AGeI working group on the Geography of Transport and Logistics. More specifically, the contributions in this issue can be traced back in part to the conference "Transport and logistics between global challenges and local development", held in Trieste on November 22 and 23, 2023, and they are just a small part of the results of this meeting.

In fact, the Trieste Conference – organized by the undersigned and intended as a handover in the coordination of the group from Giuseppe Borruso to Marcello Tadini of the AGeI Group "Geography of Transport and Logistics" – aimed to provide an opportunity for interdisciplinary debate with the participation of colleagues from various national and international institutions in the fields of geography, economics and law, as well as territorial stakeholders interested in these issues. Two round tables addressed the theme: "Maritime transport between local and global challenges. Geoeconomic and geopolitical aspects" and "Logistics and supply chain. Scenarios for logistics chains between de-globalization and re-globalization"; two thematic sessions also delved into the topics of "Smart cities, ports & regions. City, port, region relations; last mile distribution, accessibility and internal areas" and "Sustainability and transport. Circular economy and energy transition". The discussions around these events, during the Trieste days and in the subsequent period, have resulted in several contributions that, in this volume, address a varied and articulated series of topics, independent of each other but broadly centred on the themes of current debate on the issue of transport and logistics.

A first point of view is an expression of the reflection on the issues related to the development, in a broad sense, of territories linked to the articulation of the logistics and transport system. In this sense, the contribution on the relationship between hinterland and foreland (Prezioso) is positioned, recalling the port and coastal function as a line of demarcation and development for the two parts (sea and land) of the same context. In line with this, focusing on the land side, is the contribution on SEZs - Special Economic Zones (Esposito), on which there is ongoing debate and regulation, from a political and economic point of view, on their ability to attract and create local development, especially in the contexts of Southern Italy, specifically in the Italian case. To align with the maritime component, the contribution on the specialization and characteristics of the Italian port system (Tadini), between containerization and the development and consolidation of other traffic categories. The sea side is also joined by the energy issue, with reflections on the opportunities, risks, and hypotheses regarding the use of alternative fuels in shipping (Di Fazio, Palmentieri, Paradiso). On the subject of mobility, moving on to consider collective mobility, the review is concluded by the virtuous case of innovation in on-demand transport systems for areas with weak demand in the case of Friuli Venezia Giulia (Mazzarino).

Giuseppe Borruso (Università degli Studi di Trieste)

Research priorities of the AGeI Group "Geography of Transport and Logistics"

The AGEI Group "Geography of Transport and Logistics" intends to investigate the main research topics in the field of transport geography, finding a study segment in the relationship between the transport of goods and people in relation to territory and space. The aim of the Group is to bring together the different research paths in the field of transport geography in a common space of comparison and research.

In general, this discipline intersects issues such as trade flows, communication and connectivity systems, tourism, demography, migration phenomena, politics, society and culture. Few disciplines are able to put the role of territory and space so much at the centre of their scientific interests.

The research areas that the Working Group is focusing on concern the freight transport in relation to territory and space. This is a topic that is particularly declined in terms of globalisation, international trade, supply chains and complex systems and networks. Innovations and trends relating to urban transport are of definite scientific interest in the future, with particular reference to the freight sector in terms of sustainability, assisted by the theme of great interest represented by the development of transport infrastructures and networks.

A further topic of great relevance is the issue of the energy transition that is affecting the transport and mobility sector in particular (transition to electric mobility), calling into question the analysis of the repercussions on the geography of energy sources and world geopolitics and geo-economics. The energy transition, again, brings with it the issue of environmental sustainability and the effects on the environment, primarily in terms of pollutant emissions and global climate change.

The theme of transition also strongly recalls the strategic relevance of modal shift choices and the development of intermodal transport in the transfer of goods and people, which have increasingly become essential issues in modern public policies.

Connected to the phenomena of globalisation is the area of study concerning maritime transport and port activities. The processes triggered by this phenomenon are causing profound territorial transformations, in the areas of exchange (ports and retro-port regions) and in the places of destination, changing the logics of production and transport in a reticular way. Lastly, in the sphere of maritime-port transport and its territorial values, the role played by the cruise sector is worth mentioning, in its twofold value, linked to its importance in terms of tourism, its economic impact in the territories affected by the flows, as well as environmental and safety issues.

Marcello Tadini (Università degli Studi del Piemonte Orientale)

ARTICLES

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A TRANSDISCIPLINARY APPROACH FOR ASSESSING ALTERNATIVE FUELS IN SHIPPING

Clara Di Fazio*
Stefania Palmentieri**
Maria Paradiso***

Abstract

Maritime transport drives global trade, but it is facing pressure to address environmental concerns, notably greenhouse gas emissions. This study explores and critically assesses the complexities of adopting alternative fuels in maritime operations, considering the technological advancements, market dynamics, operational challenges, and broader societal needs. Using a transdisciplinary approach, it integrates diverse knowledge sources and value perspectives, advocating for participatory methodologies involving industry stakeholders and local expertise. Through assessing various fuel types for their viability in maritime transportation, this research contributes to sustainability and innovation dialogues in the maritime industry.

Keywords: maritime industry, sustainability, innovation, alternative fuels, transdisciplinary, interdisciplinary.

1.Introduction

Maritime transport is the predominant mode for commodity exchange with more than 80 per cent of worldwide trade in goods facilitated through maritime routes (Balcombe at al., 2019; Mallouppas and Yfantis, 2021; Gore et al., 2022). Maritime transport plays a pivotal role in the interconnectedness of the global economy, carrying the crucial responsibility of ensuring the secure and dependable transportation of essential commodities. These commodities include grains, food products, raw materials for energy production and consumer goods, among others.
The efficiency and security of maritime transportation networks are essential for sustaining global trade and ensuring the availability of essential goods to populations worldwide (OECD, 2021; Popek, 2024).

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The paper is the result of the joint work of the authors. However, Clara Di Fazio wrote paragraphs 2 and 3; Stefania Palmentieri wrote paragraph 4 and Maria Paradiso wrote paragraphs 1 and 5.

The strategic management of maritime services is primarily concerned with optimising fleet efficiency while ensuring the delivery of a satisfactory level of service to attain profitability. However, planners and operators often overlook the externalities linked with maritime operations, particularly the environmental consequences (Lee et al., 2024; Popek, 2024).

Recently, the maritime industry is under increasing pressure to significantly mitigate Greenhouse Gas (GHG) emissions, as stipulated by the ambitious targets set forth by the International Maritime Organization (IMO). In October 2018 (MEPC 73), the IMO endorsed a subsequent programme with scheduled evaluations in 2023 to assess adherence to the timelines established in the initial strategy and subsequently formulate an updated strategy. Effective from 1 January 2020, IMO regulations implemented a worldwide restriction on the sulfur content of marine fuels utilised by vessels operating outside the specified emission control areas.

The shipping sector faces the significant challenge of choosing alternative fuels to mitigate carbon emissions amidst the ongoing evolution of renewable fuels and their associated infrastructure (Gilbert et al., 2018; Lee et al., 2024; Bilgili, 2021; Zincir, 2022). Shipping enterprises opt for multiple fuels to diversify their energy sources. A projected common scenario by 2050 entails ships fuelled concurrently by various iterations of diesel/biodiesel, methane, methanol and ammonia (Lee et al., 2024; Popek, 2024; Duong et al., 2024; Zamboni et al., 2024). This envisages a substantial escalation in operational complexity compared to the current fleets, where the simultaneous management of multiple fuel types is infrequent.

Compliance with the regulations and pragmatic considerations influence the technological viability of alternative fuels. Numerous investigations have explored the environmental impact of maritime operations and have proposed mitigation strategies, including the adoption of cleaner fuels and the implementation of slow steaming techniques (Crist, 2009; Eide et al., 2009; Franc and Sutto, 2014; Rehmatulla et al., 2017; Xing et al., 2020; Zisi et al., 2021; Ju and Hargreaves, 2021; Ammar, 2018; Cullinane and Cullinane, 2013).

Slow steaming entails the deliberate reduction of a vessel's operational speed, which, in addition to reducing operational expenses, has the potential to significantly decrease emissions (Karountzos et al., 2024; Cariou, 2011; Woo and Moon, 2014; Yin et al., 2014; Pastra et al., 2021; Degiuli et al., 2021), which is especially pertinent for high-speed vessels (Psaraftis et al., 2009).

The potential implications of adopting alternative marine fuels on human health and occupational safety require considerable scrutiny due to the associated risks, such as toxicity, flammability and explosiveness. These risks could present significant occupational health hazards for both ship crews and shore personnel, underscoring the need for thorough evaluation and appropriate safety measures (Popek, 2024; Duong et al., 2024).

As the review of relevant studies demonstrates, while the literature regarding the environmental and economic impacts of the maritime industry, assessing emission and monitoring shipping environmental externalities, this study considers the integration of techno-scientific innovations into society that implies a complex network of interactions and mutual understandings. Thus, the present paper's aim requires an approach that integrates diverse knowledge sources and value perspectives to effectively address the inherent complexities.

Given the relevance of the topic, this study aims to assess the interplay among technological advancements, market dynamics, operational challenges regarding the choice of alternative fuels, industry stakeholders and the requisites extending beyond the production domain.
In the authors' evaluation, a transdisciplinary (Kaiser and Gluckman, 2023) approach is needed: A scientific approach based on critical active listening and continued interaction with the local and national knowledge that includes diverse actors and viewpoints for the co-production of knowledge.
The authors' perspective delineates and emphasises the pivotal significance of professional or experiential expertise, while notably acknowledging the invaluable contribution of local knowledge systems. Therefore, the present paper adopts the authors' interdisciplinary and transdisciplinary approach for comparing various fuel types as well as clarifies and criticises the attributes for their integration into maritime transportation.
The paper is organised as follows: Section 2 provides the Methods; section 3 provides the Results; section 4 presents the Discussion; section 5 presents the conclusions.

2. Methods

This research aims to co-produce some reflections that have matured within an interdisciplinary and transdisciplinary discourse that, by accommodating the variety of themes and approaches, is deemed necessary for criticising and comparing the pros and cons in the use of alternative fuels in shipping. Interdisciplinary research transcends disciplinary boundaries to collaboratively address complex problems and significantly contribute to scientific advancements. Transdisciplinary research integrates diverse knowledge sources and perspectives to address societal challenges and produce actionable knowledge for improvement. This approach promotes innovation by fostering extensive collaboration and involving stakeholders in creating actionable scientific knowledge. Within this approach, the key drivers include recognition of the world's complexity, the need for actionable knowledge and the requirement for knowledge production to transcend disciplinary boundaries. The authors' transdisciplinary research emphasises collaborative partnerships, empowering stakeholders through participatory approaches that include diverse actors and viewpoints (see Kaiser and Gluckman, 2023 on transdisciplinary).

This research, which was conducted from April to October 2023, is based on a qualitative approach aimed at producing a framework related to shipping and alternative fuels. The interdisciplinary and transdisciplinary methodological approach can be categorised in two main steps:

1. *Workshops*. The authors organised a series of seven workshops at the University of Naples "Federico II", Italy, featuring prominent experts from the maritime sector. These workshops, which were held from April to May 2023, were conducted in a classroom for up to 200 people, aimed to identify sustainability solutions and the challenges encountered by shipping activities mitigating GHG emissions. The participants, approximately 150, included Port Authorities, maritime entrepreneurs, research and economics managers as well as academics specialising in shipping. The meetings were planned by defining the research objectives and assessing the specific expertise of the participants. Then, an agenda was created for sessions dedicated to different topics, with designated times for presentations and debates. During the

workshops, slides, videos, documents, and nautical charts were shared with the participants to enhance their understanding of the presented content. Discussions and exchanges between speakers and participants were encouraged in a spirit of constructive criticism. After each meeting, a summary of the main points discussed during the workshop was prepared.

The workshops therefore facilitated the exchange of diverse perspectives, fostering a reflective process that identified avenues for further research in a dynamic and collaborative learning context. Authors meticulously planned the workshops, curated participants, documented data and remained mindful of the ethical considerations and power dynamics inherent in qualitative research methods (for detailed methodology, see Hay and Cope, 2021). The workshop topics encompassed the electrification of engines and ports, naval gigantism, and sustainability innovations in shipping, use of alternative fuels and organizational, structural and economic implications as well as the role of policy in implementing a possible green turn. The outcomes of the workshops elucidated the primary drivers that will shape the future prospects of sustainable shipping, particularly regarding alternative fuels.

2. *Interviews*. Interviews play a crucial role in examining the power dynamics and social phenomena inherent in geographical contexts. Interviews are considered a tool of a qualitative methodology that is useful to understand and criticise, in this context, what the policy lines are used by stakeholders and what is feasible.

Interviews aimed at defining the pros and cons of sustainable alternative fuels as well as analysing the viability of policy initiatives. The selection of the stakeholders was based on the relationship between their interest in specialising in maritime research and economics and their influence on the system as regards sustainability.
Four semi-structured interviews were conducted with maritime entrepreneurs, ship owners and tugboats operators, specialising in maritime research and economics (Propeller Club, Association that develops maritime activities for the purpose of improving human relations and international relations - interviewed 1; Neapolitan Tugboats - interviewed 2; RINA S.p.A. - Italian Naval Register - , Private Company committed to simplifying complexities with a focus on energy transition, sustainability and digitisation in the maritime sector - interviewed 3; SRM, Research Center for Economic Studies related to Intesa Sanpaolo Banking Group - interviewed 4). Stakeholders were chosen based on their experience and expertise in shipping. Their ‘weight’ and influence on strategic decisions, technological innovation, or environmental policy choices was considered. Another selection criteria were based on the diversity of the operators’ affiliation to the various shipping sectors: freight transport, shipbuilding, port logistics, economic experts to obtain a comprehensive overview of sectoral dynamics and to ensure that the results were relevant, accurate and applicable. The interview topics included the electrification of engines and ports, naval gigantism, and alternative fuels, and they are presented in Table 1.

TOPICS	RESEARCH THEMES
Electrification of engines and ports	• Extension of the use of electric motors in navigation and the electrification of ports • Pros and cons of electrification
Naval gigantism	• Advantages of the development of naval gigantism and fuels consumption • Sustainability differences between small and large vessels
Alternative fuels	• New fuels being used • Type of vessels that prefer to use alternative fuels • Differences in the use of fuels for different types of vessels • Differences, in terms of emissions, between large and small ships using a traditional fuel with an alternative fuel • Long-term vision for the adoption of alternative fuels • Technical challenges in the adoption of alternative fuels • Infrastructure to support the transition to alternative fuels • Barriers in the adoption of alternative fuels

Table 1: Topics covered in interviews with experts in the maritime sector. Source: Authors' elaboration.

Throughout the interviews, a note-taker was present in the virtual room, despite recordings being made with the providers' permission (Kitchin and Tate, 2000; Miles et al., 2019). Immediately after the interviews, the authors transcribed them closely to minimise the risk of bias.

3. Results

This research examines how technological advancements, market dynamics, operational challenges and stakeholder perspectives shape the adoption of alternative fuels in maritime transport.

Firstly, workshops emphasise the challenging role of maritime traffic in reducing GHD in the growing need of globalised trade.

The workshop topics encompassed a comprehensive exploration of key areas in maritime innovation. These included the electrification of engines and ports, advancements in naval gigantism, and sustainability innovations within the shipping industry. Additionally, the workshop delved into the utilization of alternative fuels and examined the organizational, structural, and economic implications associated with their adoption. Furthermore, the discussions highlighted the critical role of policy in driving and implementing a potential green transition within the sector.

The workshop resulted in several significant outcomes. Participants identified electrification as a pivotal driver for reducing emissions, with particular emphasis on the importance of upgrading port infrastructure to support this transition. In the realm

of naval gigantism, the findings suggested that while larger vessels offer economies of scale, they also present challenges in terms of environmental impact and require more advanced technological solutions to mitigate these effects.
The discussions on alternative fuels underscored the necessity of a diversified energy mix, where no single fuel solution is likely to dominate. Instead, a combination of biofuels, hydrogen, and ammonia, among others, was deemed essential to meet the varying demands of different shipping routes and vessel types. This transition, however, would require significant organizational restructuring and investment in new technologies, highlighting the importance of aligning economic incentives with environmental goals.
The role of policy was recognized as a cornerstone in enabling the green transition. Participants agreed that clear, consistent, and supportive regulatory frameworks are crucial to drive industry-wide adoption of sustainable practices. Moreover, the workshop stressed the need for international cooperation to ensure that policies are harmonized across borders, thereby avoiding regulatory discrepancies that could hinder progress.
Overall, the workshop provided a clear roadmap for the maritime industry's transition towards sustainability, emphasizing the need for integrated approaches that combine technological innovation, policy support, and economic incentives.
It emerged, therefore, that analysis conducted by industry operators evaluates various energy sources for ship propulsion. The main information in shipping challenges refers to cold ironing, LNG, batteries, hydrogen, ammonia and nuclear power that are analysed for their usability, compliance, safety, range, upgradability, energy efficiency, operational constraints, cost and public perception.
Secondly, the sustainability of maritime transport in interviews has emerged as a focal point for regulatory policies, reflecting concerns about the industry's environmental impact and efficiency (Interviewed 1, 2, 3). Rapid global economic and geopolitical shifts further complicate matters, necessitating a holistic approach to address the challenges in the maritime and port sectors.
Shipowners and stakeholders engaged in shipping operations regularly express dissatisfaction with the overall inadequacy of regulatory frameworks in the sector and the bureaucratic processes involved in their administration (Interviewed 1). The new policies are very often introduced to protect interests that conflict with those characteristics of an efficient sea transport system (Interviewed 3, 1).
In addition, recent rapid changes in world economic and geopolitical scenarios are following dynamics that are not compatible with the shipping and port sectors (Interviewed 1, 2, 3). Ships, ports and inland port infrastructures are strictly integrated into a complex logistics chain. It is not possible to modify ports without considering the corresponding modifications to be adopted on calling ships and inland infrastructures. The capital intensity of shipping projects requires large-scale and long-lasting investments, taking decades to be realised and conveniently amortised to impose system stability (Interviewed 3, 4). A radical change of technologies, imposed not for technical but rather for "political" reasons, could be incompatible with that (Interviewed 2, 4). The shipping industry, therefore, emphasises that any regulation that dictates unsustainable technical solutions and implementation times must be avoided.
This occurs when restrictions are placed on the sources or methods of producing a ship's propulsive energy before the necessary resources to comply with the imposed

change are widely available on the market (Interviewed 1, 2). Impositions are also applied to a limited part of the world market (based on nationality, flag or geographical area), e.g. as is done in countries where environmental lobbies are the most active. In a globalised market open to competition between neighbouring regions, the effect is, therefore, only devasting for the shipping of those nations that are obliged to be ecologically 'virtuous' (Interviewed 1, 2, 3). The others remain exempt from rules that are uneconomic and difficult to implement with the result that there is little benefit to the environment of the entire planet (Interviewed 2, 3, 4).

4. Discussion

The adoption of alternative fuels for maritime transport offers both advantages and obstacles. It is crucial to identify the barriers to their use.
Firstly, based on the results of the workshops and interviews, critically processed considering the authors' geographical expertise, it emerged that factors such as fleet composition, ship technical specifications, operational dynamics, investment needs, environmental impacts and geographical considerations significantly affect the feasibility of using alternative fuels.
A thorough evaluation of the pros and cons of each possible solution is, therefore, indispensable. For this reason, it was therefore elaborated an assessment framework which allows and clarifies the changes of choices towards the most effective and reliable solutions to contain the risks and undesirable damage that a generalised change would entail.
Thus, the authors' framework assesses the generated stakeholders' information in a critical and reflexive way which stems from following a transdisciplinary approach.
The framework considers the following evaluation criteria:

- **Usability** – Suitability and availability for an effective adoption without excessive technical, economic, cultural, or geopolitical difficulties to achieve rapid impact on the existing shipping sector.
- **Compliance** – Level of adoptability taking into consideration the complexity of the international and national regulatory requirements and standards of the present shipping industry, without requiring the scrapping of the global fleet and/or existing port facilities.
- **Safety** – Level of safety risks in case of a large utilisation for ships, port facilities, seafarers, port workers and the environment.
- **Range** – Suitability for adequate onboard energy storage (in kWh) to allow long navigations without the need for inefficient refuelling stops.
- **Upgradability** – Suitability to benefit from technological advances in retrofit without great technical difficulty or cost.
- **Energy efficiency** – Effective direct and indirect overall environmental impact reduction (not only greenhouse gas emissions) compared to fossil fuels in case of long-term adoption for: production, consumption, waste disposal, scrapping, etc.
- **Operational constraints** - Difficulty or operational complexity for an effective adoption on a global scale in relation to compliance with safety and labour regulations for the entire shipping sector.

- **Cost** – Economic sustainability for investment in research, adaptation of existing resources (technical and human) ashore and onboard, production, distribution, and utilisation in the whole shipping sector.
- **Green recognition** – The perception and appreciation by the "environmentalist" public opinion of the eco-compatibility, even beyond its actual effectiveness, of this solution for an adequate containment of the environmental impact of the maritime sector.

To facilitate the comparison between the different alternative fuel “solutions”, based on the opinions and assessments expressed by stakeholders, elaborated thanks to the geographical expertise of the authors, an increasing “weight” (from 1 to 3) was assigned to the relative relevance of the different “evaluation criteria”. For each alternative fuel, an increasing “score” (from 0 to 5) was then assigned, as a measure of the suitability of the “solution” to satisfy the individual “evaluation criteria”. The sum of the product of each “weight” by the relative “score” assigns to the “solution” a total synthetic “score” to be compared with that of the other “solutions”.
For further synthetic reference, the total scores of Marine Gasoil (MGO) and a hypothetical “perfect” alternative fuel that satisfies all the evaluation criteria with the maximum “score” have been calculated. As shown in the following Table 2, with respect to the different types of alternative fuel existing on the market today and usable for maritime transport, it is not possible to identify a single “ideal” solution as sustainable and effective for the decarbonization of the sector. The authors propose the following critical evaluations and results in the choice of alternative fuels or a mix.
Cold ironing emerges as a mature solution to achieve effective emissions reductions in port areas at a reasonable cost and time, with a good impact on local communities. **LNG** offers significant emissions reductions, but faces logistical and safety complexities, limiting its applicability to specific vessel types and routes. **Batteries** appear promising for short-range voyages alternating with long stops at shore-based charging docks and therefore face infrastructure challenges and some safety issues. **Hydrogen, Ammonia** and **Bio-Fuel** appear to be environmentally friendly alternatives, but their widespread adoption depends on improvement in production methods and infrastructure development. **Nuclear power**, while offering emission-free energy, raises social and safety concerns and requires large upfront investments.
Technological innovation, including wind energy integration and carbon capture technologies, holds promise for further reducing emissions. Information and Communication Technologies (ICT) play a pivotal role in enhancing efficiency, sustainability, and compliance within the maritime sector. Advanced software solutions enable real-time monitoring, route optimisation and fuel management, while digital platforms streamline supply chain operations.
ICT also supports education and research initiatives aimed at promoting sustainability in maritime transport, facilitating training on fuel management practices, and fostering the development of new technologies.

EVALUATION CRITERIA	WEIGHT
Usability	3
Compliance	2
Safety	2
Range	3
Upgradability	1
Energy efficiency	2
Operational constraints	1
Cost	3
Green recognition	3
	20

	Ammonia	**Score**
Usability	Technology ready for direct use with adaptation of existing gas diesel engines and, unlike hydrogen, can be stored at room temperature at a pressure of less than 20 bar or at ambient pressure in cryogenic (-33°C). The technology for producing ammonia is available as the first engines for its use should be available soon	**4**
Compliance	Medium with regulation that aims to contain the corrosivity when in the liquid state and the harmfulness of NOx emissions after combustion through the adoption of catalytic filters	**3**
Safety	The problematic ammonia-related emissions are mainly nitrogen oxides (NOx), which can be harmful to the environment and human health. However, these harmful emissions can be reduced by installing catalytic exhaust systems that can convert nitrogen oxides to nitrogen (N2) in a safer and less harmful manner	**3**
Range	Pretty good: energy density equal to half that of LNG with similar space occupied by the tanks	**4**
Upgradability	Good both for installation on board and for the availability of production plants on land thanks to the continuous studies and improvements on the efficiency of the engines and the production of ammonia from renewable sources	**4**
Energy efficiency	As a fuel ranks second in terms of global efficiency, after biofuels and before hydrogen.	**3**
Operational constraints	Moderate, with a typical supply chain for dangerous chemical products	**4**
Cost	High investments for the design, construction, and operation of both the ship and the land-based systems and installations	**3**
Green recognition	Considered one of the most promising low-emission fuels because burning it only produces water vapour and nitrogen. Greenhouse gas emissions are significantly reduced compared to other more traditional fossil fuels	**4**
		71

	Bio-Fuel	**Score**
Usability	Mature for large use as compared to traditional fossil fuels, only the "bio" origin changes but the composition is practically the same and therefore it can be used in the same systems with very few adaptations	**5**
Compliance	Easy	**4**
Safety	Safe	**4**
Range	Very good	**4**
Upgradability	poor due to the already mature motoring, storage and distribution aspects	**2**
Energy efficiency	Very high - the production of CO2 and unburned emissions is practically the same as fossil fuels, emissions of other pollutants are nearly absent with an efficient production process	**4**
Operational constraints	Moderate - Similar to other fossil fuels	**3**
Cost	Moderate - Similar to other fossil fuels	**3**
Green recognition	Given its similarity to fossil fuels, it is seen today as not very "green". It will be even less popular in the future because its geopolitical and social disturbing aspects, with the conversion of vast areas for food production (corn, sugarcane, palm oil, cottonseed, sunflowers, wheat, soybean) into energy production dedicated monocultures	**2**
		71

	Cold Ironing	Score
Usability	Ready for wide use on any type of ship with minor retrofit adaptations	**5**
Compliance	Easy	**4**
Safety	Safe	**4**
Range	NIL - To be used when moored in port	**0**
Upgradability	Poor due to the already mature technology onboard. To be improved and implemented the production and distribution network ashore	**3**
Energy efficiency	High - depends on the ecological efficiency of generating electricity on land	**3**
Operational constraints	For high electrical powers there is a need for extensive mechanization or robotization of the connection and disconnection system of the power cables	**2**
Cost	High investments to equip ports and docks for the supply and distribution of huge electrical power	**3**
Green recognition	Much appreciated by seafarers, passengers, port and backport communities, for the total absence of emissions (smoke and noise) when compared to the use of ship generators	**4**
		63

	Batteries (Hybrid/Electric)	Score
Usability	Recently introduced in the naval sector with specific legislation in the development and standardization phase but mature in the automotive sector	**3**
Compliance	Shipping specific rules in the development and standardization phase	**3**
Safety	Although considered a low-risk system, there is a strong concern about fires from sudden overheating in automotive installations	**4**
Range	Reduced. limited energy stored in the batteries compared to the volume and weight occupied. the hybrid solution preferred with predominant power developed by traditional engines/generators for medium/long range navigation.	**2**
Upgradability	Very high due to the continuous improvement of batteries in terms of size, weight, capacity and charging times.	**4**
Energy efficiency	High (as for cold ironing) in fully electric systems; depending on the battery/generator power ratio of hybrid systems which still achieve a more efficient operating regime (peak-shaving)	**3**
Operational constraints	Moderate, for large battery installations specific skills may be required from crew electricians	**4**
Cost	High for battery system onboard and as for cold ironing onshore in fully electric systems; depending on the battery/generator power ratio of hybrid systems	**4**
Green recognition	Much appreciated by seafarers, passengers, port and backport communities as cold-ironing; depending on the battery/generator power ratio of hybrid systems	**4**
		67

	Hydrogen	Score
Usability	It is a very promising fuel but still in the pre-industrialization phase in the shipping sector. It can be stored at room pressure with cryogenic technology (-253°C).	**2**
Compliance	Complex installation and use rules both on board and on land	**3**
Safety	Very high accident risks onboard and ashore which limit its practical use only to ships intended to serve ports/areas with Hydrogen storage and production facilities	**3**
Range	Good - energy density is relatively low compared to LNG.	**4**
Upgradability	Good both for the aspects of on-board installation and for the availability of production plants on land thanks to the continuous studies and improvements of fuel cells and the production of hydrogen through hydrolysis from renewable sources instead of natural hydrocarbon gases	**3**
Energy efficiency	Poor since most hydrogen fuel is non-renewable natural gas with huge CO2 emissions. In the future, production should take place via hydrolysis from renewable sources	**2**

Operational constraints	Extremely complex onboard and with military-like installation safety standards ashore	**3**
Cost	Very high investments for the design, construction, and operation of both the ship and the land-based systems and installations	**3**
Green recognition	Very high as there are no polluting emissions during use with production of only water vapor and electricity. The polluting phase is relegated to the production of hydrogen on land since an industrial process based on fossil fuels is still used extensively.	**5**
		64

	LNG	**Score**
Usability	Technology ready for direct use with normal diesel engines; cryogenic storage on board and on land is very complex	**3**
Compliance	Complex installation and use rules both on board and on land	**2**
Safety	High accident risks which limit its practical use only to ships intended to serve LNG production and storage plants	**2**
Range	Very good	**5**
Upgradability	Poor due to the already mature motoring aspects and the very demanding storage and distribution investments	**2**
Energy efficiency	While the production of CO2 is practically the same as traditional fuel, emissions of unburned fuel and other pollutants are very low	**3**
Operational constraints	Extremely complex with military-like installation safety standards	**2**
Cost	High investments for design, construction, and operation of both the ship and the land-based systems and installations	**1**
Green recognition	It is generally perceived as an energy source with low environmental impact far beyond its real eco-compatibility with an excessively high risk of possible catastrophic accidents	**4**
		57

	Nuclear power	**Score**
Usability	Currently limited in the commercial field due to the intrinsic danger of this type of solution, very interesting for sporadic maintenance/refuelling (every 10-15 years) and easy replacement of the reactor at the end of life	**3**
Compliance	Extremely complex due to the lack of regulatory uniformity at a global level	**1**
Safety	Hi risk, similar to that of a small nuclear power plant on land	**2**
Range	Unlimited (replacement of nuclear batteries every 10/15 years)	**5**
Upgradability	Very high thanks to the rapid technological progress that extended use in the commercial shipping field would favour with the same configuration of the rest of the ship and the land and port facilities	**5**
Energy efficiency	Considerably high, with complete absence of any form of emissions into the atmosphere and water (obviously without considering accidents to on-board and land systems)	**5**
Operational constraints	Extremely complex onboard and with military installation safety standards ashore	**2**
Cost	Very high investments for the design, construction, and operation of both the ship and the land-based systems and installations	**3**
Green recognition	Perceived as extremely risky with nations that consider it a virtuous energy source and others (like Italy) that still see it as too risky (accidents during operation and disposal of radioactive waste) and therefore legally prohibited	**3**
		65

Marine Diesel Oil (5*3+5*2+4*2+4*3+2*1+1*2+3*1+4*3+0*3)	**64**
"Perfect" alternative fuel (5*3+5*2+5*2+5*3+5*1+5*2+5*1+5*3+5*3)	**100**

Table 2: Alternative fuels based on the evaluation criteria.

Source: Authors' elaboration.

Digital platforms facilitate the management of the entire maritime fuel supply chain, from the producer to the end consumer. The use of blockchain and other distributed technologies is also increasing the transparency, security, and efficiency of transactions within the industry.

5. Conclusions

In today's energy landscape, policies have been frequently characterised by a pressing need to transition from fossil fuels to sustainable sources, with solutions that often rely on a one size solution. However, there is no one-size-fits-all solution which is applicable to all nations or situations.

In this paper, the authors discussed that the choice of alternative fuels in maritime transport is influenced by several factors, including political, geographical, and technological constraints. In addition, considerations such as vessel type, maritime traffic, crew qualifications and space availability onboard play a crucial role in determining alternative energy solutions. This study highlights the complexities and challenges associated with the adoption of alternative fuels in maritime transport. Through workshops and interviews, it became evident that while alternative fuels such as LNG, hydrogen, and ammonia offer significant potential for reducing greenhouse gas emissions, their successful implementation depends on overcoming various operational, regulatory, and infrastructural barriers.

Workshops revealed the critical importance of electrification, naval gigantism, and alternative fuel diversification, each presenting unique opportunities and obstacles. Moreover, the pivotal role of policy was emphasized, as regulatory frameworks need to be carefully designed to support the industry-wide adoption of sustainable practices without stifling innovation or imposing undue economic burdens.

Interviews with stakeholders revealed deep-seated concerns regarding the adequacy and fairness of current regulatory approaches. The shipping industry's dissatisfaction with bureaucratic inefficiencies and the misalignment of policies with the practical realities of maritime operations were prominent themes. Thus, in the authors' proposed methodology, policies should more deeply and fruitfully engage in carefully assessing operators and then carrying out policies favouring a mix of alternative solutions, thereby successfully implementing sustainable practices within the maritime sectors. The need for international cooperation and harmonized regulations emerged as essential to avoiding competitive disadvantages and ensuring the global effectiveness of environmental initiatives.

The authors developed a transdisciplinary path for critically assessing insights from industry practitioners. This collaborative approach enhances the probability of successfully implementing sustainable practices within the maritime sector.

Moreover, critical assessments of recent innovations as well as the identified limitations and prospects for their future application in ship propulsion, key priorities and challenges are discussed, including the need to address specific training and cultural requirements within the maritime industry to facilitate the transition to sustainable practices, the need for a collaborative approach among operators, community research and institutions for new distributed digital infrastructure.

Ultimately, the transition to sustainable maritime transport requires an integrated approach that balances technological innovation, economic viability, and regulatory

coherence. As the industry confronts rapid global economic and geopolitical changes, it is crucial to develop strategies that are both environmentally responsible and economically sustainable. This research provides a roadmap for stakeholders, emphasizing that collaboration, flexibility, and forward-thinking policies are key to overcoming the challenges and seizing the opportunities presented by this critical shift towards greener maritime practices.

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