Multi-perspective techno-economic comparison of decarbonization scenarios in the maritime transport sector

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Abstract

The maritime transport sector acts as the backbone of world trade and is facing an imperative and challenging goal: to navigate towards sustainability, in the quest for decarbonization. High hopes are placed on alternative marine energy sources. This study presents a comparative assessment of alternative marine energy sources and power system combinations, based on a multi-criteria decision analysis (MCDA) framework that focuses on the perspective of different decision makers' (DM) profiles: Environmentalist, Investor and a Balanced one. The combinations are compared in terms of quantifiable parameters including (i) Well-to-tank (WTT) energy intensity, (ii) well-to-wake emissions, (iii) volume per trip, (iv) mass per trip, and (v) total costs in two scenarios - including and excluding carbon taxation; and qualitative criteria, namely (vi) energy vector production technology readiness level (TRL), (vii) power system TRL, and (viii) infrastructure, all estimated from the literature. Five different vessels are analysed in the scope of this research: a container ship, a general cargo ship, a ro-pax ship, a pax-ferry, and a fishing trawler. The study reveals that e-methanol paired with an internal combustion engine (ICE) stands out as the choice for eco-focused maritime decisions across all vessel types (Environmentalist perspective), followed by e-LNG+ICE. Nevertheless, current carbon taxes have limited sway in pushing Investor DMs towards green alternatives for large ships, suggesting a necessity for aggravating taxation. Notably, a Balanced decision-making approach consistently highlights top sustainable options across all vessel types, suggesting that combining environmental and cost factors effectively guides maritime transport towards decarbonization.

Key words: *alternative energy sources, maritime transport sector, multi-criteria decision analysis, GHG emissions, decarbonization, sustainability*

1. Introduction

The global maritime sector stands as a cornerstone of international trade, with over 80% of the world's trade volume being transported across the seas. By 2021, seaborn transport had ferried more than 11 billion tons of goods, marking an impressive growth of 85% since the start of the century (UNCTAD Stat, 2022). Yet, the maritime industry's reliance on heavy fuel oil (HFO) for almost 79% of its total fuel consumption in 2018 presents a pressing concern (IMO - International Maritime Organization, 2020). The HFO, recognized as a major pollutant and greenhouse gas (GHG) emitter, has raised alarming concerns for both environmental and human health (Abdul Jameel et al., 2019). Due to such dependencies, the shipping sector's contribution to global CO_2 emissions is International Maritime Organization (IMO) charted a strategic plan in 2018, pledging a reduction of GHG emissions by at least 50% by 2050, benchmarked against 2008 levels (IMO, 2018).

In an era where climate change concerns are intensifying, it is paramount that the maritime transport sector takes definitive steps towards sustainable energy alternatives. The present research seeks to rise to this occasion, aiming to pinpoint the most suitable energy vector and power system combination in different types of vessels, to enable decarbonization within marine transport. Leveraging a Multi-Criteria Decision Analysis (MCDA) based model, the study casts its net wide, encompassing requirements, and by analyzing the perspective of different decision maker (DM) profiles. By doing so, it hopes to provide a compass for a diverse set of stakeholders, ranging from investors to policymakers and environmental advocates, in their navigation towards decarbonization strategies.

At the heart of this study lies a techno-economic comparison of selected energy vectors and promising power systems, considering both new builds and retrofit possibilities. With a focus on five distinct vessels across a presumed 30-year operational span, the research offers a deep dive into how varying typical voyages and onboard fuel capacities might sway the best choices for energy vector and power system combinations.

1.1. The Maritime Transport Sector

The maritime industry is compartmentalized into 13 major ship categories, ranging from Container ships that transport containers to Fishing Vessels that catch and transport fish. In 2021, a breakdown by type revealed that Fishing Vessels (21.8%), Tugs (16.6%), General Cargo Ships (13.6%), Oil and Chemical Tankers (12.0%), and Bulk Carriers (10.8%) comprised the bulk of the fleet by number, making up almost 75% of the total. However, when assessed by gross tonnage, Bulk Carriers (34.4%), Oil and Chemical Tankers (25.4%), and Container Ships (18.0%) dominated, representing over 75% of the fleet's deadweight (Equasis, 2021). The heavy dependence of the maritime transport sector on HFO and other fossil fuels has adversely impacted the environment. Accounting for 2.89% of global CO_2 emissions in 2018, the shipping sector's emissions trajectory is concerning, with a record 847 million tons of CO_2 being emitted by April 2022. Focusing on the heaviest emitters, Container Ships stand out as the leading polluters (United Nations - UNCTAD, 2022). Consequently, several technologies are emerging as possibility to help this sector to mitigate emissions.

Dual-fuel internal combustion engines (ICE): Developed in 1980 (Karim, 1980), dual-fuel engines use an alternative fuel with a small amount of diesel for injection. These engines have recently gained traction in maritime applications (Benvenuto et al., 2017; Marques et al., 2019; Tadros et al., 2023), with notable manufacturers like MAN Engines and Wärtsilä producing them (MAN Engines, 2022; Wärtsilä, 2023). **Lithium-ion batteries**: Mainly proposed for short-sea navigation, Li-ion batteries (LIB) appear to be the frontrunners for full electrification. A study comparing various battery types found LIBs to be the most cost-effective and environmentally friendly option (Perčić et al., 2022). Moreover, integrating LIBs with hybrid systems has also proven to reduce CO_2 emissions significantly (Peralta P. et al., 2019). **Fuel cell (FC) technology**: FCs are emerging as a tool for decarbonization, especially for near-zero emissions when used with the right fuel. They generate electricity via electrochemical reactions. Proton exchange membrane fuel cells (PEMFC) and Sulphur Oxide Fuel Cells (SOFC) are gaining attention in the marine sector due to their efficiency, durability, and operational benefits (Elkafas et al., 2023).

1.2. Promising alternative energy vectors

Between 2000 and 2020, there was a significant increase in the research into cleaner marine fuels, with an annual growth rate of 15.8% (Ampah et al., 2021). The maritime sector is considering a broad range of energy solutions due to the variety of vessel types and operational profiles – one size does not fit all (Bergek et al., 2021). The future of maritime fuels is poised to include liquefied natural gas (LNG), methanol, ammonia, hydrogen, and synthetic diesel derived from renewables. While LNG is currently perceived as a transitional fuel (Balcombe et al., 2021; Lagemann et al., 2022; Lindstad & Rialland, 2020), methanol is fast gaining traction due to its commercial viability (Islam Rony et al., 2023; Oloruntobi et al., 2023). Ammonia is projected to become a mainstream option in the mid-term, by 2030 (Korberg et al., 2021; Mallouppas et al., 2022), with hydrogen expected to dominate in the long-term, by 2050, although challenges related to storage and infrastructure persist (Balcombe et al., 2021; Gray et al., 2021). The role of synthetic diesel will closely depend on the fuel's production supply chain, since it is still too expensive to produce compared to its peer fuels at today's state of the art (Schemme et al., 2017). Additionally, the electrification of ships using Li-ion batteries for short navigation has emerged as a potential solution to reduce emissions (Perčić et al., 2022).

LNG is viewed as a transitional maritime fuel in Europe, with infrastructure expansion evident (DNV GL, 2022). Its appeal stems from reduced CO_2 emissions, but its high methane content and methane slip during combustion pose concerns (Burel et al., 2013). While LNG infrastructure has expanded, with 354 LNG-powered ships in operation by 2022 (DNV GL, 2022), its environmental benefits are debated due to methane emissions (Balcombe et al., 2021; Pavlenko et al., 2020).

Methanol has become a contender as a maritime fuel over the last decade, especially after the International Maritime Organization's 2021 guidelines (MSC.1/Circ. 1621) regarding the use of methyl or ethyl alcohol as fuel for ships (DNV GL, 2023). If produced sustainably through biomass, biogas, or renewable electricity, it promises carbon neutrality (Gray et al., 2021), but it also presents challenges like toxicity (Oloruntobi et al., 2023; Verhelst et al., 2019). Production is predominantly from natural gas, but interest is growing in carbon-neutral methods (Tian et al., 2022). E-methanol, a form of green

CH3OH, is derived through the integration of captured CO2 and hydrogen produced by using renewable electricity to electrolyze water. The sources of CO2 can originate from industrial carbon capture processes, encompassing bioenergy with carbon capture and storage (BECCS)1 and direct air capture (DAC)2 (Lloyd's Register, 2023). By 2023, 25 methanol-powered ships were operational (DNV GL, 2022), and its use in fuel cells for propulsion is under exploration (Mandra, 2020).

Ammonia's potential fuel applications have been revitalized recently, although its use in this capacity dates to the 19th century (NewScientist, 2013). Its production can be carbon-intensive unless powered by renewables, and while promising, challenges like production costs and safety remain (Giddey et al., 2017; Ye et al., 2017). No commercial ammonia-powered ships exist yet, but projects like NoGAPS are underway to develop them (Fahnestock et al., 2021).

Hydrogen, especially green hydrogen, is spotlighted for its potential in maritime applications (Atilhan et al., 2021; Ortiz-Imedio et al., 2021; Van Hoecke et al., 2021). However, challenges related to global regulations, storage, and production costs persist (Grigoriev et al., 2006; Manabe et al., 2013). Hydrogen is categorized by its source, with "green hydrogen" being derived from renewables. Storage remains a concern due to hydrogen's low density, but projects like HyShip, encompassing a PEMFC are aiming to demonstrate its feasibility (HyShip, 2022). In 2022, innovations like the Norled ferry MF Hydra, powered by hydrogen, indicate progress towards this fuel's maritime adoption (Mandra, 2022).

1.3. MCDA on alternative maritime energy vectors

Multi-criteria decision analysis (MCDA) provides a structured approach to select the most suitable option from a set of pre-selected alternatives, especially in complex scenarios with multiple criteria involved (Jahan et al., 2016; Jahan & Edwards, 2013). Ren & Lützen (2017) developed an MCDA method to evaluate sustainable energy sources for shipping but limited their study to only three energy vectors. In contrast, Hansson et al. used a broader approach, incorporating various stakeholder groups to assess seven fuel types, offering insights into real-world stakeholder preferences. Aspen & Sparrevik (2020) explored the uncertainties in maritime fuel selection, combining two decision models and applying them to a Norwegian passenger ferry, highlighting the strength of all-electric propulsion. Meanwhile, Law et al. (2021)conducted an exhaustive comparison of 22 alternative fuel pathways but could have benefitted from considering varied decision maker (DM) perspectives.

To sum up, while MCDA plays a crucial role in examining maritime energy alternatives, there's a gap in assessing marine alternative fuels paired with varied power systems, considering various DM perspectives, applied to different case study vessels with contrasting purposes and operating profiles. The present research aims to bridge this by considering diverse criteria, contrasting stakeholder views, and different fuel-power system pairings across different vessels.

2. Methodology

2.1. Case study description

The study introduces a Multi-Criteria Decision Analysis (MCDA) model aimed at directing key stakeholders in the maritime industry, such as investors, manufacturers, environmentalists, and academics, toward suitable alternative energy and power system combinations to decarbonize the sector. The analysis encompasses five distinct vessels (Minnehan & Pratt, 2017), each with their unique regular voyages (**Error! Reference source not found.**):

Emma Maersk: Once the world's largest container ship with a capacity of 11,000 TEU, it sails from Tanjung Pelepas port in Malaysia to Port Said in Egypt.
Spiegelgracht: A Dutch general cargo ship capable of carrying containers and bulk cargo. Its journey starts at Zeebrugge port in Belgium and ends at Philadelphia, U.S.A.
Pride of Hull: A large ro-pax ship that can hold 1,360 passengers and 1,380 vehicles. Its typical route is from Hull port in England to Rotterdam port in the Netherlands.
Zalophus: A smaller pax-ferry offering one-hour bay tours starting and ending at the Port of San Francisco, U.S.A.
Northwestern: A fishing trawler spending extended

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[1] Technology where CO2 from a biogenic source released during energy generation from biomass is captured and stored (Gough & Upham, 2010).

[2] Technology that captures and storages CO_2 directly from air (McQueen et al., 2021).

durations at sea. Its journey is from Seattle to Dutch Harbor, U.S.A.

Table 1 *- Selected vessels' characteristics, adapted from (Minnehan & Pratt, 2017)*

Type	**Container ship**	**General cargo**	**Ro-pax**	**Pax-ferry**	**Fishing trawler**
Name	*Emma Maersk*	*Spiegelgracht*	*Pride of Hull*	*Zalophus*	*Northwestern*
ME Power (MW)	80.08	12.1	37.8	0.8	0.95
Fuel capacity (m3)	15000	1880	1000	29,5	174
Voyage distance (nm)	5005	3431	211	11	1707
Voyage time (h)	256	271	11,9	1	217
Energy per trip (MWh)	9240	881	237	0,485	58

Various energy vectors are considered, ranging from fossil-based (denoted with 'f-') to electric renewable-based (denoted with 'e-'), alongside multiple power systems, such as internal combustion engines (ICE), proton exchange membrane fuel cells (PEMFC), sulphur oxide fuel cells (SOFC), and lithium-ion batteries – the full scope of analysed combinations is described in table. This research aims to evaluate the techno-economic performance of each energy vector and power system combination throughout a ship's operational life, not just a single voyage. This includes analysing OPEX costs, energy vector costs, and the impact of potential carbon taxation over a three-decade period, which is the assumed lifespan for the selected vessels.

2.2. Scenarios' definition

This study examines two sets of energy vector-power system combinations for a vessel's 30-year lifespan. The "retrofit set" starts with ships powered by heavy-fuel oil (HFO) with an internal combustion engine (ICE) in the first decade, assuming a 2020 commission. By 2030, these vessels retrofit to an alternative energy combination. This set simulates the decisions for vessels initially powered by fossil fuels, looking to decarbonize. Only the initial construction costs for the HFO ship are considered in this scenario. The "new set" maintains an alternative energy system for the vessel's entire 30-year life without retrofitting. This set's construction costs differ from the default, accounting for the chosen alternative energy combination. Both sets are analysed under two scenarios: excluding carbon taxation (Scenario A) and including carbon taxation (Scenario B), penalizing higher GHG-emitting fuels, promoting sustainable energy choices.

MCDA Model Formulation

2.3.1. Criteria definition

The study uses a Multi-Criteria Decision Analysis (MCDA) based model for a thorough evaluation of alternative energy vectors and power systems for various vessels, considering technical, economic, and environmental factors. Overall, a total of eight criteria are considered for evaluation, based on various significant characteristics of an ideal maritime fuel and power system combination (Law et al., 2021); the total costs criterion differs for each scenario: including and excluding carbon taxation – table 3.

Infrastructure, a qualitative criterion, uses a four-level ranking: IV indicates a fully developed infrastructure, III implies a somewhat mature setup with minor changes needed, II suggests a less mature infrastructure requiring significant updates, and I represents almost non-existent infrastructure. This classification is informed by research from Hansson et al. (2019) and Xing et al. (2021). Infrastructure availability varies across vessel types due to their unique operational roles and voyage types. Large vessels, like container ships, often dock in major ports connected to industrial zones, granting them easier access to certain fuels. However, they might struggle with obtaining sufficient electricity for vast battery arrays. In contrast, smaller passenger ferries operating in coastal areas might find it challenging to get specific fuels like LNG, but they typically have simpler energy needs and better access to other fuel types. Therefore, infrastructure performance scores will differ depending on the vessel's size and type.

Table 2 *- Energy vector and power system combinations description, adapted from (European Sustainable Shipping Forum, 2022)*

Combination	Energy vector	Pre-treatment	Energy Conversion	After treatment	Power distribution
HFO+ICE	HFO, 3.5% sulphur	HFO heating (up to 60º)	ICE CI[5]	Scrubber[6], SCR[7], soot filter[8]	ICE direct propulsion
f-LNG+ICE	LNG fossil	Evaporation	ICE SI[9]	-	ICE direct propulsion
e-LNG+ICE	e-LNG: H_2 from RES + flue gas CO2	Evaporation	ICE SI	-	ICE direct propulsion
e-diesel+ICE	Synthetic diesel (EN15940): H_2 from RES + flue gas CO2	-	ICE CI	SCR, soot filter	ICE direct propulsion
f-methanol+ICE	CH_3OH fossil (from NG)	DF treatment	DF ICE	-	ICE direct propulsion
e-methanol+ICE	e-CH3OH (95%) + diesel (5%): H_2 from RES, DAC[10] CO_2	DF treatment	DF ICE	-	ICE direct propulsion
e-methanol+PEMFC	e-CH_3OH: H_2 from RES, DAC CO_2	Reformer CH_3OH	LT PEMFC	-	FC electric propulsion
f-NH3+ICE	NH_3 fossil (95%) + diesel (5%): from NG	Evaporation, DF treatment	DF ICE	SCR, soot filter	ICE direct propulsion
f-NH3+PEMFC	NH_3 fossil (from NG)	NH_3 cracker	LT PEMFC	-	FC electric propulsion
f-NH3+SOFC	NH_3 fossil (from NG)	-	SOFC	-	FC electric propulsion
e-NH3+ICE	e-NH_3 (95%) + diesel (5%): H_2 from RES, N_2 capture	Evaporation, DF treatment	DF ICE	SCR, soot filter	ICE direct propulsion
e-NH3+PEMFC	e-NH_3: H_2 from RES	NH_3 cracker	LT PEMFC	-	FC electric propulsion
e-NH3+SOFC	e-NH_3: H_2 from RES	-	SOFC	-	FC electric propulsion
e-LH2+ICE	e-LH_2 (96%) + diesel (4%): H_2 from RES	Evaporation, DF treatment	DF ICE	SCR, soot filter	ICE direct propulsion
e-LH2+PEMFC	e-LH_2: H_2 from RES	Evaporation	LT PEMFC	-	FC electric propulsion
EU-mix+batteries	EU mix electricity stored in a Li-ion battery	-	-	-	Battery electric propulsion

Table 3 *- Criteria considered in the selection of alternative fuel and power system combinations.*

Focus aspects	Criteria	Description
Environmental	WTW Emissions	Refers to the lifecycle GHG emissions (well-to-wake) during the vessel's lifetime (kt CO_2). Quantitative criterion.
Economic	A - Total Costs excluding carbon taxes	Total costs (A) encompass construction costs, retrofit costs, onboard technology costs (€/kW), tank costs (€/m^3), fuel costs and carbon taxes during the vessel's lifetime. Quantitative criterion.
	B - Total Costs including carbon taxes	Total costs (B) encompass construction costs, retrofit costs, onboard technology costs (€/kW), tank costs (€/m3), and fuel costs during the vessel's lifetime. Quantitative criterion.
Technical	Energy Intensity (TTW)	Refers to the tank-to-wake energy intensity of transport, measured in energy consumed per ton transported per kilometre travelled (kWh/(ton.km)). Quantitative criterion.
	Volume per trip	Refers to the volume needed per trip for each combination, includes fuel storage and FC/ batteries volume when applicable. Quantitative criterion.
	Mass per trip	Refers to the mass (kg) needed per trip for each combination, includes fuel mass and FC/ batteries mass, when applicable. Quantitative criterion.
	Energy vector production TRL	Technology readiness level (TRL) of the energy vector production according to the European Commission principles, retrieved from MARIN (2022). Quantitative criterion (1-9).
	Power system TRL	Technology readiness level (TRL) of the power system according to the European Commission principles, retrieved from MARIN (2022). Quantitative criterion (1-9).
	Infrastructure	Refers to compatibility with existing infrastructure, including ports and fuel infrastructure, and distribution, based on the research of (Hansson et al., 2019; Xing et al., 2021). Qualitative criterion (I-IV ranking, from worst to best).

2.3.2. Normalization

Normalization is essential to standardize varying performance values, making them comparable on a common scale. In this study, the linear scale transformation (using the max method) was used for normalization (Chakraborty & Yeh, 2007). Criteria were divided into two categories: beneficial (higher values are desirable) and non-beneficial (lower values are preferable). Only three criteria, including energy vector production TRL, power system TRL, and infrastructure, were considered beneficial. The normalization technique adjusted these criteria using equation 1, while non-beneficial criteria were adjusted using equation 2, where xij is the performance value of the i-th alternative for the criterion j, Max(xj) is the maximum performance value for criteria j among all the alternatives, and nij is the normalized value.

Volume constraint is dictated by each vessel's fuel capacity. For the "new set" of vessels, a 15% buffer was added to the fuel capacity to ensure sustainability. If any energy vector-power system combination surpassed this buffer, its volume criterion score would be null. However, for the "retrofit set," only the vessel's original fuel capacity was considered. Any alternative that didn't fit within this capacity was excluded from the final scores.

Additionally, the WTW Emissions criterion is benchmarked against the default combination's emissions (HFO+ICE). If an alternative combination surpasses the default emissions, its score for that criterion is null. This methodology supports the study's aim of identifying sustainable energy combinations to decarbonize the maritime sector.

$$n_{ij} = \frac{x_{ij}}{Max(x_{ij})} \tag{1}$$

$$n_{ij} = 1 - \frac{x_{ij}}{Max(x_{ij})} \tag{2}$$

2.3.3. Weightage and final scoring

The weight assigned to each criterion represents its significance to the decision maker. In this study, criteria weightage is crucial because it heavily influences the final scores, indicating the most fitting combination for each scenario. For this dissertation, the weights were determined based on assumptions reflecting the perspectives of two hypothetical decision makers: an environmentalist who values low GHG emissions and an investor who prioritizes cost. There was also a balanced decision maker who equally values WTW Emissions and Total Costs. The criterion with the highest weight is highlighted in green – table 4.

To obtain the final scores for every alternative combination in each scenario, the weighted sum method was applied, obtained using equation 3, where $w_{j,m}$ is the weight of criterion *j* according to the decision maker *m*, and *i* represents each combination.

$$Total\ Score_{\,i} = \sum_{i=1}^{31}\sum_{j=1}^{7} w_{j,m} \times n_{ij} \quad , \quad for\ m=\{1,2,3\} \tag{3}$$

Table 4 - *Weightage of each criterion according to three types of decision makers*

	Energy Intensity	WTW Emissions	Volume per trip	Mass per trip	Total Costs	TRL energy vector production	TRL power system	Infrastructure
Environmentalist	15%	35%	5%	5%	10%	15%	5%	10%
Balanced	10%	**20%**	10%	10%	**20%**	10%	10%	10%
Investor	10%	10%	10%	5%	35%	10%	10%	10%

3. Results and Discussion

The study examined five maritime vessels, grouping them by size into two categories. Larger vessels included the container ship, general cargo ship, and ro-pax ship, while the pax-ferry and fishing trawler represented the smaller category – Table 5 shows the summarized top three results. To focus the findings, detailed results were primarily analysed for the container ship, a major long-distance cargo transporter, and the pax-ferry, a smaller vessel for short passenger and vehicle bay tours, emphasizing the study's interest in both large-scale and coastline vessels.

For the container ship, the environmentalist DM showed a clear preference for renewable sources, particularly e-NH3+SOFC, irrespective of the cost, as expected. Meanwhile, the investor DM, even when considering carbon taxation, predominantly favoured fossil energy vectors due to cost effectiveness, although this preference could shift towards more sustainable options with a more severe carbon taxation. Nonetheless, when emissions and costs are given equal weightage (balanced DM), a combination like e-LNG+ICE rises to the top, with no preference for fuel cells or batteries due to their unsuitability for large, long-journey ships.

The pax-ferry differed somewhat. From the environmentalist's perspective, options like e-methanol+ICE were consistently fevered. The investor DM showed a more balanced approach compared to the container ship, leaning towards greener options such as EU-mix+Li-ion, emphasizing the suitability of Li-ion batteries for shorter voyages. For the balanced DM, green energy sources remained the top three choices.

Environmentalist DMs consistently favour e-methanol+ICE across vessel types, underscoring its potential for sustainability across varied voyages and vessel types.

Investor DMs usually prefer fossil fuel options, particularly for longer voyages. However, smaller vessels like pax-ferries and fishing trawlers could sway investor preferences towards green alternatives.

Fuel Cells (FC) currently aren't top contenders, possibly due to their current costs, efficiency, and lifespan. Future advancements might elevate FCs in rankings.

Liquefied Hydrogen (LH2) also doesn't rank among top choices presently, but ongoing research and potential future infrastructure make it a notable mention for future maritime energy.

Consistency between larger vessels (like the container and general cargo ships) have almost identical best-ranked options across all decision maker types. This indicates that larger vessels that endure longer voyages might have a relatively narrow range of optimal energy vector and power system combinations from different decision maker perspectives.

The Balanced DM's top three options for each vessel type consistently prioritize "green" alternatives. Another key observation is that there are no retrofit options in the best scoring options of this DM. This suggests that it is possible to achieve a more sustainable maritime transport sector by equally considering WTW emissions and total costs in the decision-making process, and that building a new vessel powered by a sustainable energy vector is more attractive than retrofitting after a decade.

4. Conclusion

In the quest to decarbonize the maritime transport sector, the present study delved into identifying the most suitable combinations of energy vectors and power systems across varied decision criteria. The investigation uncovered significant insights into the preferences and priorities of different decision makers.

For the Environmentalist DM, green alternatives, particularly e-methanol combined with an ICE, stood out as a prominent choice, offering a notable reduction in greenhouse gas emissions. However, a transition to such an alternative comes with financial implications, seeing a surge in costs when disregarding carbon taxes. On the other hand, the Investor DM leans more towards fossil fuel solutions, especially for larger vessels. This leaning indicates the limited impact of current carbon taxation in nudging investors towards more sustainable choices, underscoring the need for more stringent measures to incentivize green shifts.

The perspective of the Balanced DM provides a holistic view, merging both environmental impact and economic feasibility. Through this lens, green choices, including e-LNG combined with ICE and e-methanol with ICE, frequently emerge as leading options. Interestingly, the study found that fuel cell-based solutions did not feature among the top choices for either the Investor or the Balanced decision maker, pointing to the current challenges associated with FC technology, especially for larger vessels with longer journeys. Similarly, LH_2 was also absent from the leading choices, highlighting its current limitations as a prominent solution for decarbonization. However, it is worth noting the ongoing developments in LH_2 as a fuel and its potential future role in maritime transport.

Future work could focus on hybrid energy solutions that contemplate differing power systems for main and auxiliary engines, tailored to their operational nuances. The current uncertainty surrounding the costs and states of nascent technologies, coupled with the broad generalization that analysed vessels mirror the global merchant fleet, poses challenges. Addressing these concerns may require more sophisticated data collection techniques and stochastic models for uncertainty management. Future endeavours should also factor in the cost implications of lost cargo in new energy combinations, particularly the effects of the assumed 15% fuel capacity buffer. While this research employed a simplified MCDA model, future work might benefit from a more intricate MCDA framework, incorporating real industry stakeholder perspectives for a more nuanced understanding, akin to the approach suggested by Hansson et al. (2019). Integrating life-cycle assessment techniques with MCDA, as evidenced by (Campos-Guzmán et al., 2019), could provide a more comprehensive framework for evaluating sustainable energy systems in subsequent investigations.

In essence, this research offers a significant contribution to the maritime sector's imperative decarbonization goal. By leveraging the insights derived from the MCDA-based model and accounting for diverse decision maker perspectives, the maritime industry's stakeholders are better equipped to make informed choices. The path forward calls for the strategic adoption of alternative energy vectors and power systems, underpinned by a delicate balance of environmental, technical, and economic considerations. The maritime sector's sustainable future hinges on timely actions, fostering collaboration, spurring innovation, and wholeheartedly embracing greener alternatives.

Table 5 - Resume table with the top 3 performers' final score for each vessel in both scenarios (A- without carbon taxation, and B- with carbon taxation)

		No Carbon Tax (A)		With Carbon Tax (B)	
Vessel	**Decision Maker type**	**Option**	**Score**	**Option**	**Score**
CONTAINER	Environmentalist	N: e-methanol+ICE	68,8	N: e-methanol+ICE	69,4
		N: e-NH3+SOFC	66,1	N: e-NH3+SOFC	66,1
		N: e-LNG+ICE	64,2	N: e-diesel + ICE	64,7
	Balanced	N: e-LNG+ICE	68,8	N: e-methanol+ICE	68,9
		N: e-methanol+ICE	67,5	N: e-LNG+ICE	69,3
		N: HFO+ICE	66,4	N: e-NH3+ICE	64,7
	Investor	N: HFO+ICE	73,2	N: HFO+ICE	66,3
		N: f-LNG+ICE	72,7	N: f-LNG+ICE	64,9
		R: f-LNG+ICE	72,4	R: f-LNG+ICE	64,8
GENERAL CARGO	Environmentalist	N: e-methanol+ICE	68,7	N: e-methanol+ICE	69,2
		N: e-NH3+SOFC	65,6	N: e-LNG+ICE	64,2
		N: e-LNG+ICE	64,1	N: e-NH3+ICE	63,9
	Balanced	N: e-LNG+ICE	68,6	N: e-methanol+ICE	68,4
		N: e-methanol+ICE	67,4	N: e-LNG+ICE	68,8
		N: HFO+ICE	66,1	N: e-NH3+ICE	63,8
	Investor	N: HFO+ICE	72,8	N: HFO+ICE	65,6
		N: f-LNG+ICE	72,1	N: f-LNG+ICE	65,3
		R: f-LNG+ICE	71,7	R: f-LNG+ICE	63,9
RO-PAX	Environmentalist	N: e-methanol+ICE	69,5	N: e-methanol+ICE	69,4
		N: e-LNG+ICE	64,8	N: e-diesel + ICE	64,4
		N: e-diesel+ICE	64,7	N: e-LNG+ICE	64,3
	Balanced	N: e-LNG+ICE	70,0	N: e-methanol+ICE	68,8
		N: e-methanol+ICE	69,0	N: e-LNG+ICE	69,1
		N: HFO+ICE	66,7	e-diesel + ICE	64,1
	Investor	N: HFO+ICE	73,7	N: HFO+ICE	65,7
		N: f-LNG+ICE	73,0	N: f-LNG+ICE	64,4
		R: f-LNG+ICE	72,7	R: f-LNG+ICE	64,2
PAX-FERRY	Environmentalist	N: e-methanol+ICE	67,4	N: e-methanol+ICE	70,0
		N: e-NH3+PEMFC	64,4	N: e-NH3+PEMFC	67,0
		N: e-diesel + ICE	64,0	N: e-diesel + ICE	67,0
	Balanced	N: EU-mix + Li-ion	65,5	N: e-methanol+ICE	70,0
		N: e-methanol+ICE	64,9	N: e-diesel + ICE	69,2
		N: e-diesel+ICE	63,1	N: EU-mix + Li-ion	68,2
	Investor	N: EU-mix + Li-ion	64,0	N: EU-mix + Li-ion	68,7
		N: HFO+ICE	62,7	R: EU-mix + Li-ion	66,9
		R: EU-mix + Li-ion	62,7	N: HFO+ICE	64,8
FISHING TRAWLER	Environmentalist	N: e-methanol+ICE	69,2	N: e-methanol+ICE	69,1
		N: e-NH3+SOFC	66,6	N: e-NH3+SOFC	66,6
		N: e-diesel + ICE	64,3	N: e-diesel + ICE	64,1
	Balanced	N: e-methanol+ICE	68,4	N: e-methanol+ICE	68,2
		N: HFO+ICE	66,7	N: e-LNG+ICE	64,9
		N: e-LNG+ICE	65,8	N: e-diesel + ICE	63,4
	Investor	N: HFO+ICE	73,9	N: HFO+ICE	65,4
		N: f-LNG+ICE	69,5	R: e-methanol+ICE	60,6
		R: f-LNG+ICE	69,2	N: e-methanol+ICE	60,1

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