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Multi-criteria decision analysis for route prioritization of hydrogen shipping corridors to support maritime decarbonization

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The maritime shipping industry is responsible for approximately 3% of global greenhouse gas emissions. As a result, it faces growing regulatory and environmental pressure to shift towards cleaner alternative fuels. Green hydrogen, produced from renewable sources, is the possible alternative to change the maritime industry, as it represents a zero-emission alternative. Although hydrogen offers significant potential for maritime decarbonization, production costs limit its competitiveness. Considering the limitations, the purpose of this study is to prioritize international maritime cargo routes for hydrogen corridor deployment by assessing the feasibility of decarbonizing maritime cargo shipping routes between Türkiye and Hamburg using a multi-criteria decision analysis framework. Because the evaluation encompasses technical, operational, economic, and environmental factors, MCDA is necessary due to the complexity of the decision-making process. Route 2 is the most practical alternative according to the results of AHP and TOPSIS, mostly because of operational factors including engine number, refueling stops and port proximity. This suggests that while sustainability objectives (such as the Paris Agreement, CBAM) guide the shift, operational concerns play a key role in developing potential hydrogen deployment pathways. Using a simplified comparative emissions framework for route-level assessment, the results indicate that hydrogen-based pathways may contribute to lower-emission maritime transport, although operational and technical factors remain the primary drivers of route suitability. The findings show that policy objectives by themselves are insufficient to guarantee the adoption of hydrogen. It is essential that implementation strategies and route planning take operational requirements into account. Future research should look more closely at the challenges encountered in optimizing routes for the use of hydrogen in maritime transportation.

Keywords Green hydrogen, Multi-criteria decision analysis, Carbon border adjustment mechanism, Maritime decarbonization

The shipping sector, which emits 3% of the world's greenhouse gases (GHGs) and if no significant implementation takes place, shipping emissions might reach 10% of the planet's total by 2050. Therefore, it is crucial to initiate a more intensive investigation in line with the global efforts to mitigate climate change. While regulatory corporations such as the International Maritime Organization (IMO) have established long-term decarbonization targets, existing efforts fail to meet the Paris Agreement's climate objectives[1].

Adopted at COP21 in 2015, the Paris Agreement intends to mitigate climate-related threats to biodiversity, food, water, and health by limiting global warming to 1.5 °C (IPCC, 2023). The agreement aims to mitigate climate change by limiting global temperature increases to less than 2 °C above pre-industrial levels.

Despite the Paris Agreement's global climate targets, reducing shipping emissions is still a significant problem. By encouraging the use of low-carbon fuels, increasing energy efficiency, and aiming for a 40% decrease in carbon intensity by 2030, new laws like the IMO's 2023 GHG plan and the EU's FuelEU Maritime seek to reduce emissions. International shipping emissions, however, increased by 5% in 2022 and reached 2017–2018 levels, according to IEA data.

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Figure 1 shows the worldwide emissions of carbon dioxide from international shipping between 1970 and 2023. The emissions increased to 703.6 million metric tons, as they were 698.6 million metric tons in 2022. Decarbonization is both crucial and challenging because of the maritime industry's pivotal position in worldwide trade, which is highlighted by these rising emissions.

The role of the maritime industry in shipping

The maritime industry serves as a vital component to the international trade system transporting goods throughout the world, handling approximately 90% of global trade. The shipping business is critical to global trade because it connects global markets, promotes economic growth, and ensures the seamless transportation of commodities. The industry that uses both large container ships and smaller cargo vessels to transport raw materials, completed products, and commodities plays a crucial role in global trade, facilitating the transportation of diverse goods. Container ships account for about 26% of worldwide CO_2 emissions, followed by bulk carriers at 21%, oil tankers at 19%, and other vessels at 34%[2,3].

Current challenges in the maritime shipping sector

The maritime shipping business has issues related to sustainability, and technological innovation. The effects of maritime traffic on the environment are among the most urgent issues. The maritime ecosystem is still deteriorating in spite of continuous efforts to stop negative impacts. Ship emissions significantly affect the health of those who live close to port. The fact that these pollutants can lead to severe respiratory problems in addition to other health issues emphasizes how urgently cleaner industry practices and technology are needed.

Moreover, in order to shift away from the dependence on conventional fuels like oil and gas, the maritime sector is under intense pressure. In addition to addressing environmental concerns, this change aligns with international sustainable development objectives, like creating net-zero emissions zones in specific areas by 2026. The problem is to strike a balance between current economic survival and the long-term objective of sustainable development. The Sustainable Development Goals (SDGs) of the United Nations (UN) were created as an urgent call to action for all nations to prioritize policies that would bring peace and prosperity for people and the earth both today and in the future[4].

Among the 17 sustainable development goals, there are 6 main goals that are greatly connected with the maritime sector. These include SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 13 (Climate Action), and SDG 14 (Life Below Water) (Environmental Economics, 2019).

Hydrogen as a maritime fuel

Hydrogen is the possible alternative to use as an energy carrier in the maritime industry.

Hydrogen as an energy carrier

Hydrogen is a colourless, odorless, tasteless, non-toxic, non-reactive, and highly flammable gas having an extensive flammability range[5]. Of all the substances, it has the lowest atomic weight, hence it has an extremely low density in both gas and liquid form. Hydrogen can be produced from various resources such as biomass, natural gas, nuclear power or renewables like wind and solar. It acts as a flexible energy carrier and helps tackle multiple important energy challenges. Applications for hydrogen technologies include internal combustion engines (ICEs), fuel cells, and hydrogen combustion[6]. Although it usually runs less efficiently than fuel cells, hydrogen combustion produces energy and water through a reaction with oxygen, lowering greenhouse gas

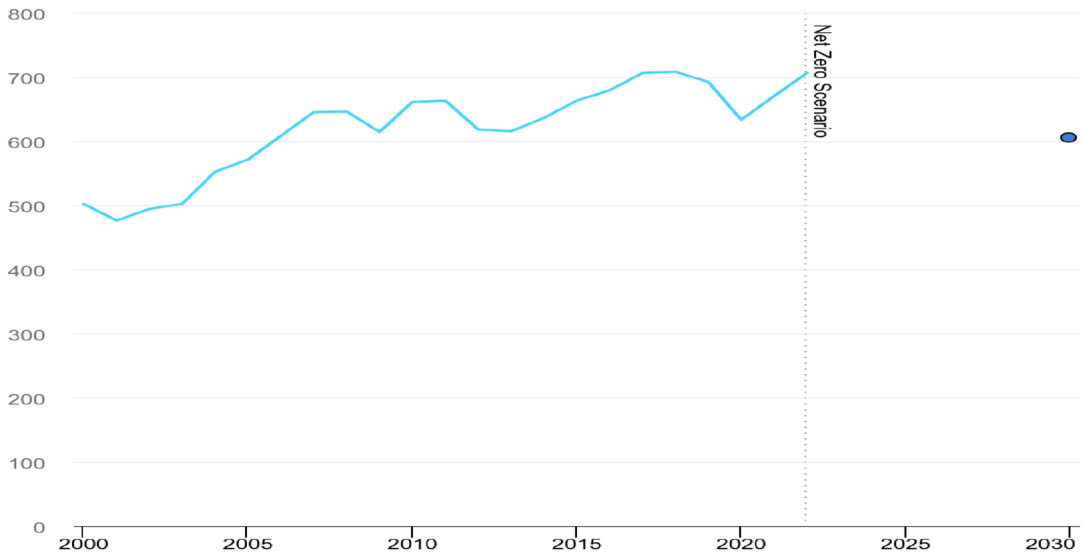


Fig. 1. Carbon dioxide emissions from international shipping worldwide from 1970 to 2023 (in million metric tons) (Source: Ref.[2,3]).

emissions as compared to fossil fuels[7]. With continuous improvements aimed at increasing their efficiency and lowering emissions, hydrogen can be used in ICEs in both spark-ignition and compression-ignition systems[8]. Fuel cells are electrochemical systems with great efficiency and low emissions that transform the hydrogen's chemical energy into electrical energy and heat[9]. But issues like high costs and vulnerability to pollutants still exist. Today, industries actively use hydrogen primarily in the refining and chemical sectors and they produce it using fossil fuels like coal and natural gas so it is responsible for important annual CO_2 emissions[10].

The EU will develop renewable hydrogen as a priority. The REPowerEU Strategy of 2022 seeks to produce 10 million tonnes while importing 10 million tonnes by 2030. Even though this target continues to be in force, real production levels are still in the early phases of scaling up. Renewable hydrogen will satisfy around 10% of the EU's energy demands by 2050, while also significantly reducing carbon emissions in energy-intensive industries and the transportation sector. Hydrogen is an important part of the EU's energy transition, supporting net-zero and sustainable development goals[11].

Types of hydrogen

According to the method of production and the energy input, three main types of hydrogen can be distinguished; green, grey or blue[12]. Currently, most of the hydrogen being produced is grey hydrogen,which means it is reliant on fossil fuels. Due to the strong existing infrastructure and low production costs, around 62% of the global H_2 production is grey hydrogen[13]. There is a significant emphasis being placed on green hydrogen as it focuses on renewable sources of energy in the future.

Grey hydrogen is the type of hydrogen produced by the vast majority of plants worldwide today. The grey hydrogen input generates a primary product by economically recreating semi-hydrogen gas with steam methane. It is mainly produced using steam methane reforming (SMR), which is still the most widely used technique for producing hydrogen today[14]. On the other hand, Blue hydrogen is the end result of attempts to decarbonize grey hydrogen production. While green hydrogen uses energy from renewable energy sources such as solar, wind, and hydro to generate hydrogen via electrolysis. It is the only method of producing low-carbon hydrogen. The entire process produces no CO_2, making green hydrogen the most ideal choice[15].

Hydrogen production methods

Depending on the primary energy source, hydrogen can be produced through a variety of pathways, which are broadly classified as renewable and non-renewable. The world's hydrogen supply is currently dominated by conventional production techniques like coal gasification and steam methane reforming (SMR), which are dependent on fossil fuels. On the other hand, decarbonization techniques are placing more emphasis on renewable-based production pathways, such as biomass gasification, electrolysis driven by renewable electricity, and thermochemical water splitting, which provide reduced lifespan emissions[16]. Renewable hydrogen production is especially important for facilitating the supply of low-carbon fuel along key shipping corridors, given the maritime sector's decarbonization goals.

ETS and CBAM: Driving the shift toward low-carbon maritime transport

Maritime transportation is a major and growing source of greenhouse gas emissions. In 2018, shipping accounted for 1,076 million tons of CO_2, about 2.9% of global emissions[17]. These emissions might rise by 130% from 2008 levels by 2050 (IMO, 2020), threatening the Paris Agreement's goals. In 2021, maritime transport made up over 124 million tons of the EU's CO_2 emissions. In July 2023, the IMO agreed on new GHG reduction goals to be reached by 2025[17].

The EU Emissions Trading System (EU ETS) now includes emissions from ships over 5,000 gross tons entering EU ports. It covers 100% of intra-EU and 50% of extra-EU voyage emissions starting in 2024[17]. Also, the Carbon Border Adjustment Mechanism (CBAM), adopted in 2023, applies carbon pricing to imports and takes full effect in 2026. While CBAM doesn't target shipping directly, it affects companies transporting goods covered by it[18]. Shipping companies will have to buy allowances under the ETS, encouraging them to adopt low-carbon fuels such as hydrogen. The EU plans to use part of ETS income to support maritime decarbonization through investment in cleaner technologies and fuels[19]. Although the literature on hydrogen applications in maritime transportation is growing, most of the studies that are now available focus on fuel supply chain optimization, port-level infrastructure development, and techno-economic viability. Although these studies provide insightful information about investment challenges and system design, they generally disregard the operational complexity present in actual maritime transportation routes. Specifically, important aspects like multi-port interactions, route structure, refueling frequency, and vessel characteristics are not appropriately addressed. As a result, there isn't a thorough route-level analytical approach in the literature that accurately captures the real-world decision-making environment that shipping operators face. Because it limits the capacity to successfully integrate hydrogen route deployment schemes with the operational and logistical realities of maritime transport systems, this limitation represents a major research gap. Thus, the lack of a methodical framework for assessing and ranking maritime shipping routes for the deployment of hydrogen routes based on operational, technological, economic, and environmental factors is the issue this study attempts to address.

Research objective

This study uses a multi-criteria decision analysis (MCDA) approach to assess and rank defined maritime cargo shipping routes for hydrogen route deployment in order to fill the identified research gap. The study offers a structured decision-making framework for making decisions that include both quantitative data and qualitative factors, which is important given the complexity of integrating hydrogen refueling infrastructure into current maritime networks. In order to support practicable hydrogen deployment methods, the proposed methodology

makes it possible to systematically evaluate and rank different pathways based on operational, technological, environmental, and economic factors.

The majority of previous research on hydrogen in maritime settings has focused on techno-economic feasibility studies, port-level evaluations, and infrastructure siting models (e.g., cost optimization, fuel supply chains, and port energy systems)[20–22]. These methods offer useful information about system design and investment requirements, but they frequently ignore the operational complexity of real shipping routes, such as vessel characteristics, the frequency of refueling, and the interactions between several ports along global trade corridors. Because a location-based perspective alone might not adequately reflect the practical realities faced by shipping operators, this indicates a gap in the state of the art.

However, this research adopts a new approach by concentrating on maritime cargo shipping routes, whereas typical studies assess hydrogen infrastructure by comparing port locations. This is due to the fact that route-level evaluation considers operational and technical factors that location-based models sometimes fail to include, like the overall distance, the number of refueling stops, and vessel compatibility. Defining the challenge in terms of route-level viability allows for an operationally appropriate selection of maritime routes for hydrogen corridor development. This change in focus is an important methodological decision that brings the study into line with actual maritime logistics between Europe and Türkiye.

The research approach fills this gap while taking into consideration the operational goals of key maritime stakeholders by prioritizing maritime cargo routes that can serve as potential hydrogen corridors. By focusing on maritime cargo shipping routes rather than just port locations, this study takes a different approach from many earlier studies. Operational and technical considerations that location-based models frequently neglect, such as total distance, the number of refueling stops, and vessel compatibility, are considered in a route-level evaluation. This route-based assessment provides a more precise and practical foundation for hydrogen corridor development than port-level analysis alone.

Therefore, by presenting a multi-criteria framework that is in line with the operational logistics of maritime transportation between Europe and Türkiye, this study aims to close the gap between location-based studies and actual operational requirements. Rather than being direct route-selection variables in the model, broader policy frameworks, such as CBAM, are seen as circumstantial drivers of decarbonization. Through supply-chain decarbonization demands and shifting trade competitiveness, CBAM has an indirect impact on fuel choices for maritime routes. The theoretical framework supports informed decision-making for early-stage hydrogen route prioritization by combining operational pathway aspects with system-level assessment.

Materials and methodology

The study performed MCDA-based economic and environment-friendly route selection for maritime industry. The followed methodology is discussed in this section.

Technology and operational assumptions

Throughout the study, a consistent set of technological and operational assumptions was used to guarantee consistency across all assessed routes and to facilitate a comparable route prioritization analysis. These assumptions aim to create a representative framework for assessing hydrogen corridor viability under present and near-term technology conditions rather than modeling a particular vessel design or potential operational configuration.

Propulsion type and efficiency assumptions

Fuel cell systems and hydrogen internal combustion engines (H_2-ICEs) are the main ways that hydrogen-based propulsion can be implemented in maritime applications. Although fuel cells have near-zero local emissions and great efficiency, there are now issues with cost, durability, fuel purity requirements, and large-scale maritime integration[9,23]. On the other hand, H_2-ICE technology is more feasible for near-term deployment scenarios because of its lower integration complexity, compatibility with current marine engine architectures, and higher technological readiness[8,24].

Therefore, a H_2-ICE-based propulsion assumption is used in this study to simulate hydrogen propulsion, reflecting current technology maturity and importance for early hydrogen corridor implementation. A constant propulsion efficiency assumption was used for all routes in order to prevent the introduction of vessel-specific optimization distortions. The analysis does not contrast different propulsion technology; rather, it concentrates on relative route feasibility. Although fuel cell systems are recognized as a viable long-term solution for maritime decarbonization, a comparison of fuel cell and H_2-ICE propulsion is outside the scope of this route-level prioritization study and will need to be covered in future vessel-level or technology-specific analyses.

Hydrogen storage form and energy basis

In accordance with the deployment of early-stage hydrogen infrastructure and current pilot applications in port and maritime settings, it was projected that hydrogen would be supplied and stored in compressed gaseous form[25]. As is common in maritime and energy systems analysis, all energy conversions were based on the lower heating value (LHV) of hydrogen (120 MJ/kg)[26,27].

Bunkering rate and refueling stop assumptions

It was considered that refueling would take place during planned port calls without adding extra waiting time particular to a given route. The number of refueling stops per route, which acts as a substitute for operational complexity and infrastructural strain, was used to indirectly treat bunkering time. Detailed terminal computations are outside the scope of corridor-level screening studies, which align with this methodology[20].

Auxiliary loads and hoteling assumptions

Auxiliary power demand and hoteling loads (i.e., energy consumption for onboard services like lighting, ventilation, and auxiliary systems during port stays) were not modeled individually because it was assumed that they were proportional across all routes and vessels. This suggests that during port visits along the analyzed routes, auxiliary engines or fuel-cell-based auxiliary systems function under similar circumstances.

This simplification makes sure that rather than vessel-specific auxiliary designs, route comparisons concentrate on relative variations in propulsion-related energy use. Previous route-level and infrastructure assessment assessments have used similar assumptions[28,29].

Criteria selection process

The evaluation criteria were chosen by thoroughly reviewing reports from the industry and scholarly literature on the development of hydrogen corridors and hydrogen-powered maritime transportation. To determine the most essential technical, operational, environmental, and economic parameters for prioritizing maritime routes suitable for hydrogen corridor deployment, the review concentrated on studies addressing maritime decarbonization, hydrogen propulsion technologies, and operational characteristics of shipping routes.

For example, maritime studies supported criteria like engine specifications and fuel demand[24,29–31], while industry platforms and logistics databases were used to inform route-level operational and infrastructure accessibility considerations[20,32]. Recent energy market data informed economic factors such as travel costs for diesel and hydrogen[33,34]. Criteria that directly addressed the operational viability of hydrogen-powered vessels, the characteristics of maritime routes that impact the need for hydrogen refueling, or the financial and ecological performance of hydrogen-powered shipping operations were included. Factors that lacked sufficient evidence support in literature or were not directly related to the viability of hydrogen corridors at the route level were excluded. This combination ensured a systematic, detailed, and comprehensive choice of criteria for assessing hydrogen refuelling infrastructure solutions and prioritizing maritime cargo routes for hydrogen corridor deployment that are both practically and theoretically applicable. Table 1 below represents the criteria chosen for evaluation in the MCDA, along with the justification for selection and the sources that back them up.

Data collection and analysis

The study considered different data for the analysis. The details of this data are discussed here.

Geographical data

Ten important maritime cargo shipping routes between Türkiye and Hamburg Port, Germany, were examined to gather the data needed to assess the criteria[32]. Instead of concentrating on a single path, the routes were chosen to reflect a wide range of shipping patterns and operational factors. To represent the various geographical and trade dynamics inside Türkiye, ports from İstanbul, İzmir, Bursa, and Tekirdağ were included. Hamburg was selected as the main destination since Hamburg is a significant European logistics hub and Germany is Türkiye's biggest export partner[35]. In addition to emphasizing different logistical challenges and hydrogen refueling requirements across routes, the inclusion of intermediate stops in countries like Belgium, France, Italy, Malta, Morocco, Portugal, and the United Kingdom further shows the complexity of actual shipping procedures. The ten chosen maritime shipping routes are shown in Fig. 2. Google Earth Pro (can be accessed from https://www.google.com/earth/about/versions/) was used to create the geographical representation of the chosen maritime routes in Fig. 2. The following steps made up the map-generation process:

1. Finding the route ports: For each of the 10 marine transportation routes taken into consideration in the study, the origin ports in Türkiye, the intermediate ports, and the destination port of Hamburg, Germany, were determined.

Criteria	Reason of choice	Reference
Engine Number in Ship (positive)	Engine number in hydrogen-powered ships directly impacts fuel demand, system reliability, and route planning	American Bureau of Shipping[30]
Engine Power (positive)	Hydrogen-powered ship engine power optimization increases efficiency and environmentally friendly maritime activities	Elgohary, M.[24]
Number of Stops per Trip (negative)	Minimizing the number of stops made in a trip, reduces the environmental impact, lowers fuel consumption, and optimizes operations	FluentCargo[32]
Hydrogen Demand per Trip (positive)	Hydrogen demand per trip is important for hydrogen-powered ship route optimization since it influences fuel requirements and operating efficiency	Mounfield et al.[29]
Site Selection (positive)	Selecting the best sites for hydrogen refuelling stations is essential to the effective growth of the network	Smid et al.[20] FluentCargo[32]
Nearest H_2 Infrastructure to Ports (positive)	Ships can refuel with hydrogen quickly and easily when refuelling infrastructure is close to ports	Smid et al.[20] FluentCargo[32]
CO_2 Emissions (negative)	Reducing CO_2 emissions is crucial for meeting international decarbonization targets of hydrogen-fuelled maritime operations	Mounfield et al.[29]
H_2 Trip Cost (negative)	Hydrogen fuel's cost per trip has an impact on its economic feasibility and ability to compete with traditional fuels	Kotowicz et al.[34]

Table 1. Criteria and justifications for evaluating hydrogen refuelling infrastructure solutions for ships.

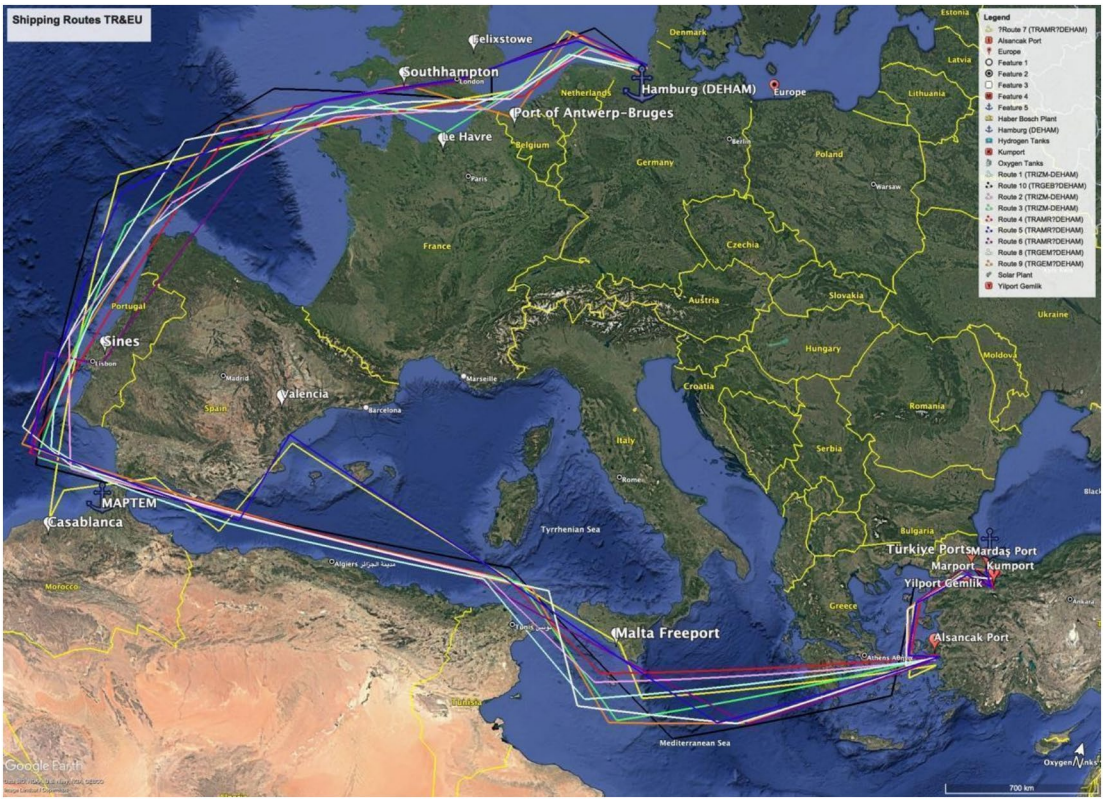


Fig. 2. Key maritime shipping routes from Türkiye to hamburg port (generated by author using google earth pro, https://www.google.com/earth/about/versions/).

2. Identifying the geographic locations: The names and most approximate locations of the recognised ports in Google Earth Pro were used to identify their geographic positions.
3. Plotting of the ports: The origin, intermediate, and destination ports were located in Google Earth Pro and marked on the map.
4. Creation of the route paths: The "Add Path" function in Google Earth Pro was used to connect the ports sequentially. Each path began at the relevant origin port in Türkiye, followed the identified intermediate port calls, and ended at Hamburg Port.
5. Representation of the ten routes: The same procedure was repeated for all ten route alternatives. The resulting paths were displayed together on a single map to illustrate and compare the geographical configurations and intermediate stops of the selected maritime shipping corridors.
6. Preparation of the figure: The map was adjusted to show all selected routes clearly, and the resulting map view was exported and used to prepare Fig. 2. Relevant data were presented in Table 2.

Although Routes 1 and 2 share the same origin port, transit port, and destination port, they were treated as separate alternatives because they are operated by different vessels with distinct technical and operational characteristics. Differences in engine power, vessel speed, and ship specifications influence hydrogen demand, emissions, and overall route performance; therefore, the two routes represent different operational scenarios within the MCDA framework.

Ship and engine data

The ship and engine data of the analysis is discussed in Table 3.

Data on cargo ship specifications, such as engine type, power, number of engines and speed were extracted from BalticShipping.com, VesselFinder.com, and MarineTraffic.com. This data is important for calculating fuel consumption, hydrogen demand, and CO_2 emissions per trip, which directly affects the planning of hydrogen refueling infrastructure. Ship speed, operating conditions, engine power, and type all play a crucial role in determining hydrogen needs and route efficiency.

Calculations of hydrogen demand and CO_2 emissions

The assessments used to calculate hydrogen demand and CO_2 emissions relied on ship and route characteristics, including ship engine power, number of engines, vessel speed, transit duration, number of stops, and total route distance. Hydrogen demand is directly influenced by ship engine power, engine configuration, and operating speed, with larger vessels generally requiring greater hydrogen quantities. Transit duration also affects hydrogen demand and associated emissions due to prolonged engine operation, while the number of stops increases

Route number	Route name	Port of origin—port of origin (TR)	Destination port (EU)	Transit country
1	TRIZM-DEHAM	TRIZMTCDD—TCDD Alsancak Port	MAPTMETM—Eurogate (TC2)	Morocco (MAPTEM)
		MAPTMETM—Eurogate (TC2)	DEHAMCTH—EuroGate Container Terminal	
2	TRIZM-DEHAM	TRIZMTCDD—TCDD Alsancak Port	MAPTMETM—Eurogate (TC2)	Morocco (MAPTEM)
		MAPTMETM—Eurogate (TC2)	DEHAMCTH—EuroGate Container Terminal	
3	TRIZM-DEHAM	TRIZMTCDD—TCDD Alsancak Port	MAPTMETM—Eurogate (TC2)	Morocco (MAPTEM)
		MAPTMETM—Eurogate (TC2)	DEHAMCTH—EuroGate Container Terminal	*FRLEH (Le Havre)*
4	TRAMR→DEHAM	TRAMRMDAS – Mardaş	MAPTMETM—Eurogate (TC2)	Morocco (MAPTEM) *TRGEB (Gebze), TRGEM (Gemlik), TRALI (Aliağa)*
		MAPTMETM—Eurogate (TC2)	DEHAMCTH—EuroGate Container Terminal	
5	TRAMR→DEHAM	TRAMRKUM—Kumport	DEHAMCTB—HHLA Burchardkai	Calls in at TRGEM (Gemlik), TRALI (Aliağa), ESVLC (Valencia), GBFXT (Felixstowe)
6	TRAMR→DEHAM	TRAMRMAR—Marport Main & West	DEHAMCTH—EuroGate Container Terminal	Calls in at TRGEM (Gemlik), TRTEK (Tekirdağ), TRALI (Aliağa), PTSIE (Sines), GBFXT (Felixstowe)
7	TRAMR→DEHAM	TRAMRMDAS—Mardaş	MAPTMETM—Eurogate (TC2)	Calls in at TRALI (Aliağa), MTMAR (Malta Freeport), ESVLC (Valencia), ESALG (Algeciras), MACAS (Casablanca)
		MAPTMETM—Eurogate (TC2)	DEHAMCTH—EuroGate Container Terminal	
8	TRGEM→DEHAM	TRGEMGMP—Yilport Gemlik & Gemport	MAPTMETM—Eurogate (TC2)	Morocco(MAPTEM) calls at TRALI (Aliağa)
		MAPTMETM—Eurogate (TC2)	DEHAMCTH—EuroGate Container Terminal	
9	TRGEM→DEHAM	TRGEMGMP—Yilport Gemlik & Gemport	DEHAMCTH—EuroGate Container Terminal	Calls in at TRALI (Aliağa), MAPTM (Tanger Med), GBSOU (Southampton), BEANR (Port of Antwerp-Bruges)
10	TRGEB→DEHAM	TRGEBYHT—Yilport Home Terminal	GBFXTTT—Trinity Terminal	Calls in at TRTEK (Tekirdağ, TRGEM (Gemlik) Transfer at Felixstowe

Table 2. Maritime shipping routes' specifications from Türkiye to hamburg port.

Route number	Ship specifications	Engine type	Engine power (KW)	Number of engines	Speed (knots)
1	MARTHA A (9,299,484)	MAN-B&W	20.638	1	22.2
	CMA CGM SALAMANQUE (9,961,348)	MAN B&W 7L70ME-C	14.490	1	20
2	MAERSK NARMADA (9,356,098)	MAN-B&W	63.910	1	22.9
	CMA CGM SALAMANQUE (9,961,348)	MAN B&W 7L70ME-C	14.490	1	20,5
3	TEOMAN A (9,226,504)	MAN B&W 7L70ME-C	15.450	1	20,5
	CMA CGM VASCO DE GAMA (9,706,889)	MAN B&W 7L70ME-C	63.910	1	22.9
4	EF OLIVIA (9,252,735)	B&W 7K80MC-C	26.270	1	20
	ESPERANCE (9,491,484)	Wartsila	14.700	1	20
5	MAERSK SEMBAWANG (9,315,226)	MAN B&W 7L70ME-C	84.313	1	25.1
6	MSC TRACY V (9,295,177)	MAN B&W 9K90MC-C	41.080	1	24.3
7	CMA CGM ISKENDERUN (9,321,902)	MAN-B&W 9K80MC-C	32.435	1	20
	CMA CGM SINTRA (9,961,362)	MAN-B&W' 6 Zylinder (6S60ME-C10-GI	14.490	1	20
8	EF OLIVIA (9,252,735)	B&W 7K80MC-C	26.270	1	20
	ESPERANCE (9,491,484)	Wartsila	14.700	1	20
9	CMA CGM TARRAGONA (9,471,214)	MAN B&W 6S60MC-C	36.560	1	24
10	MSC HONG KONG V (9,231,810)	(MAN B&W type	41.107	2	24
	MAERSK HAMBURG (9,784,312)	MAN B&W 8G95ME-C9	63.910	1	22.9

Table 3. Ship and engine data for key maritime shipping routes. (Source: American bureau of shipping[30], FluentCargo[32]).

energy requirements because of port operations and waiting times. Fuel consumption and fuel cost were not included as separate evaluation criteria in the MCDA because hydrogen demand and hydrogen cost are directly derived from these parameters, resulting in redundant information. To avoid double counting and reduce potential bias in the AHP weighting and TOPSIS ranking, only hydrogen demand and hydrogen cost were retained to represent the energy consumption and economic dimensions of the hydrogen-based transportation system. Instead of conducting a full lifecycle assessment, this study applies a simplified comparative emissions framework for route-level prioritization. Diesel emissions represent direct emissions associated with marine fuel use, while hydrogen emissions represent simplified upstream emissions associated with hydrogen production,

compression, transportation, and delivery. The purpose of this comparison is not to provide a complete lifecycle assessment but rather to provide a consistent environmental indicator for comparing alternative maritime routes within the MCDA framework. The same methodological assumptions were applied across all evaluated routes. Table 4 presents the estimated hydrogen demand (tons per trip), hydrogen trip cost (USD), and CO_2 emissions (tons) for the assessed hydrogen pathways.

Energy Content of Hydrogen = 120 MJ/kg[26].

These numbers were calculated based on the following equations:

Travel Time

$$t\,(h) = \frac{D(km)}{v\left(\frac{km}{h}\right)} \tag{1}$$

$$Effective\ propulsion\ power\ \ (load\ factor) : Peff\,(kW) = P\ installed\,(kW)\,XLF\,(-) \tag{2}$$

Load Factor assumed at 80% load.

Shaft Energy

$$Eshaft\,(kWh) = Peff\,(kW)\,Xt\,(h) \tag{3}$$

$$Eshaft\,(MJ) = Eshaft\,(kWh)\,X3.6 \tag{4}$$

Diesel mass from SFOC (recommended because it's standard in marine engines):

$$m\ diesel\,(kg) = Eshaft\,(kWh)\,XSFOC\left(\frac{kg}{kWh}\right) \tag{5}$$

Diesel volume

$$Vdiesel\,(L) = \frac{mdiesel(kg)}{\rho diesel\left(\frac{kg}{L}\right)} \tag{6}$$

where $\rho diesel = 0.84 kg/L$[36].

Diesel energy on LHV basis

$$E\ diesel\,(MJ) = m\ diesel\,(kg)\,X\ LHV\ \ diesel\left(\frac{MJ}{kg}\right) \tag{7}$$

where $LHVdiesel = 42.6 MJ/kg$[37]

Hydrogen mass required (LHV basis)

$$mH_2\,(kg) = \frac{E_{diesel}(MJ)}{LHVH_2\left(\frac{MJ}{kg}\right)} \tag{8}$$

where $LHVH_2 = 120 MJ/kg$[38].

To explicitly demonstrate the calculation process for Table 4, a worked example for Route 1 is as follows: The estimated diesel fuel consumption is 3,020,882.7 L. Applying the marine diesel density (0.84 kg/L) to maintain dimensional consistency, the required diesel mass is calculated as 3,020,882.7 × 0.84 = 2,537,541.4 kg. Using the lower heating value of diesel (42.6 MJ/kg), the total energy demand is 2,537,541.4 × 42.6 = 108,099,266 MJ. Finally, dividing this energy requirement by the hydrogen lower heating value (120 MJ/kg) yields the H_2 demand: 108,099,266 / 120 = 900,827 kg, which is approximately 900 tons. This step-by-step computation resolves the dimensional discrepancy and correctly aligns with the updated H_2 demand for Route 1 in Table 4.

Route number	Route duration (Total)	Estimated H_2 demand per ride (tons)	CO_2 emissions for diesel ships (tons)	CO_2 emissions by pathways (tons)
1	13 days 16 h	900	8,096	294
2	11 day s 15 h	836	7,512	643
3	20 days 18 h	3,435	30,854	763
4	26 days 19 h	3,757	33,768	2,026
5	16 days 12 h	4,616	41,486	6,314
6	17 days 10 h	2,985	26,823	5,045
7	30 days 3 h	2,961	26,617	8,147
8	24 days 9 h	2,082	18,719	1,059
9	15 days 21 h Direct (4 port calls)	2,421	21,758	4,541
10	14 days 5 h Via GBFXT	3,112	27,969	3,209

Table 4. Fuel, hydrogen, and emissions data for key maritime routes.

Diesel and hydrogen trips cost calculation

Costs for travel powered by hydrogen have been calculated by multiplying an average supplied hydrogen price by the hydrogen demand per route. Due to the lack of port-specific hydrogen price data, a baseline assumption of $5.025 per kilogram was made. This table (Table 5) shows the total cost of delivered hydrogen at bunkering ports, including distribution, conditioning (compression or liquefaction), and production. To maintain comparison between different choices, the same typical hydrogen price was used for all assessed routes.

Although diesel trip costs were initially estimated using a representative global marine bunker fuel price for Very Low Sulfur Fuel Oil (VLSFO), they were not included as a separate MCDA criterion because hydrogen trip costs are directly derived from the corresponding fuel costs. Including both criteria would introduce redundant information and could lead to double counting in the decision-making process. Therefore, only hydrogen trip cost was retained as the economic evaluation criterion.

The data in Table 5 were calculated using the following equations.

For Hydrogen:

$$-Trip\ Cost\,(\$) : Hydrogen\ Required\ per\ Voyage\,(kg) \times\ Delivered\ H_2\ Cost\ at\ Port\left(\frac{USD}{kg}\right) \tag{9}$$

Hydrogen price = 5.025 $/kg.

For Hydrogen:

$$-Hydrogen\ Trip\ Cost\,(\$) :\ Cost\ H2 = Hydrogen\ Demand\,(kg) \times\ Delivered\ H2\ Price\left(\frac{USD}{kg}\right) \tag{10}$$

Prices for hydrogen reflect delivered costs at bunkering ports, which include transportation and compression/liquefaction.

Emission calculations

Instead of using a full lifecycle assessment, this study's emissions evaluation uses a simplified comparative emissions framework designed for route-level prioritization. At the point of usage, green hydrogen generated by electrolysis with renewable electricity is typically linked to almost zero direct tank-to-wake CO_2 emissions. However, the infrastructure needed for hydrogen compression, transportation, storage, and distribution could still result in upstream emissions. Transport and on-site recompression using grid-average electricity can contribute to residual CO_2 emissions when hydrogen is provided in gaseous form[39]. Therefore, rather than direct combustion emissions from hydrogen use onboard ships, the hydrogen-related emissions stated in this study represent projected upstream delivery and infrastructure-related emissions. The reported hydrogen emissions should therefore be interpreted as simplified upstream supply-chain emissions rather than direct onboard combustion emissions.

Diesel emissions were calculated by the following equations:

$$Diesel\ CO2\,(kg) = Fuel\ Consumption\,(L)\,X\ 2.68kg\,\frac{CO2}{L} \tag{11}$$

$$Diesel\ CO2\,(tons) = \frac{Fuel\ Consumption(L)X\ 2.68}{1000} \tag{12}$$

Table 6 compares the CO_2 emissions of diesel ships and H_2 pathways. The comparison shows how, under the study's assumptions, traditional diesel emissions differ from the predicted upstream emissions linked to hydrogen supply channels. Green hydrogen emits almost no direct combustion emissions, but energy requirements for transportation, infrastructure, and compression may still result in upstream lifecycle-related emissions. Despite pipeline-related emissions contributing to the carbon footprint, hydrogen remains more advantageous in terms of environmental impact (shown in Fig. 3).

The prominent difference in CO_2 emissions between diesel ships and hydrogen pathways shows the critical role of hydrogen as a fuel source in the maritime sector. To achieve the goals of global emissions reduction

Route number	H_2 trip cost (German price $5.025)
1	4,522,500
2	4,200,900
3	17,260,875
4	18,878,925
5	23,195,400
6	14,999,625
7	17,879,025
8	10,462,050
9	12,165,525
10	15,637,800

Table 5. Cost of H_2 trips for key maritime routes.

Route number	CO_2 emissions for diesel ships (tons)	CO_2 emissions by H_2 pathways (tons)
1	8,096	294
2	7,512	643
3	30,854	763
4	33,768	2,026
5	41,486	6,314
6	26,823	5,045
7	26,617	8,147
8	18,719	1,059
9	21,758	4,541
10	27,969	3,209

Table 6. Comparative CO_2 emissions for diesel and hydrogen pathways.

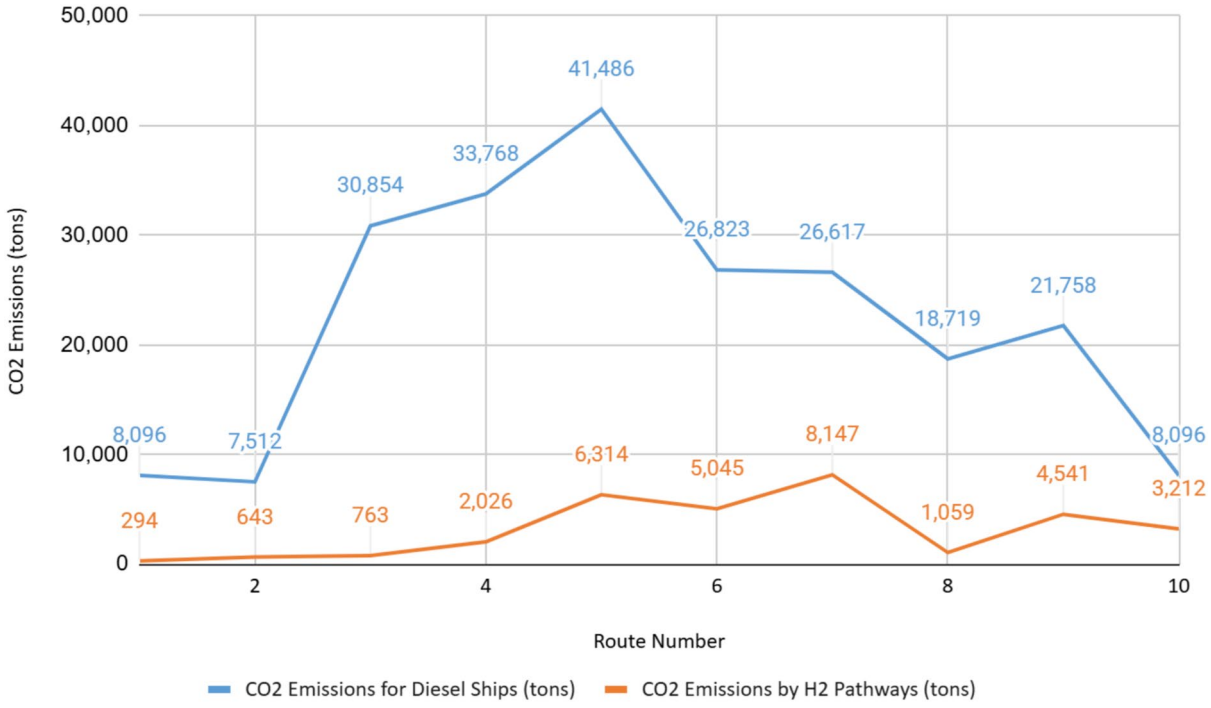


Fig. 3. The CO_2 emissions of both diesel ships and H_2 pathways.

targets and fasten the shift to low-carbon maritime transportation, the importance of establishing a hydrogen refuelling infrastructure is crucial.

Infrastructure site selection

Selecting strategic locations for hydrogen refuelling infrastructure near ports is crucial to minimize transportation costs and CO_2 emissions. Keeping a short distance between production/storage sites and ports improves supply chain efficiency and supports maritime decarbonization. Proximity ensures the infrastructure is accessible, cost-effective, and aids the transition to hydrogen as a sustainable maritime fuel. The hydrogen refuelling infrastructure details used in the study was represented in Table 7.

Methodology

The integrated Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approach is used to evaluate the result. The AHP is used for weight determination and the TOPSIS is used to find the optimal rank.

Multi-criteria decision analysis

MCDA, known as a subset of Multi-Criteria Decision Making (MCDM) is a method used to assess and rank different sets of criteria in the processes of decision-making[40]. It evaluates different criteria that may be quantitative or qualitative, and focuses on aiding decision-makers in choosing the best alternative among the criteria involved[41]. The generic steps followed in MCDA:

Route number	H_2 infrastructure	Distance from port (Km)
1	Bandırma, Balıkesir	290
	Agadir, Morocco	20
2	Bandırma, Balıkesir	290
	Agadir, Morocco	20
3	Bandırma, Balıkesir	290
	Agadir, Morocco	20
4	Bandırma, Balıkesir Agadir, Morocco	629
	Agadir, Morocco	20
5	Bandırma, Balıkesir Castellón de la Plana, Valencia Felixstowe Port	587
6	Bandirma, Balikesir Felixstowe Port Sines H_2 Project	509
7	Bandirma,Balikesir Import to Malta Port Castellón de la Plana, Valencia Agadir, Morocco	868
	Agadir, Morocco	20
8	Bandırma, Balıkesir Agadir, Morocco	339
	Agadir, Morocco	20
9	Bandırma, Balıkesir Southampton Port Port of Antwerp-Bruges	324
10	Bandırma, Balıkesir Felixstowe Port	321
	Felixstowe Port	2

Table 7. Hydrogen refuelling infrastructure sites and their distances from ports for selected maritime routes.

1. Specifying the Problem: Identifying the problem and objectives of the decision.
2. Identifying the Criteria: Determining the criteria that will be used and assessing the alternatives.
3. Establishing Alternatives: Listing alternatives that will be evaluated according to the criteria used.
4. Evaluating Alternatives: Weighing each alternative based on how well it matches the defined criteria.
5. Decision Making: Analyzing the results in order to choose the ideal best alternatives[42].

The integration of hydrogen refuelling infrastructure into the current maritime shipping routes involves logistical, technical, and regulatory issues. Because of this, choosing the best maritime routes for the early deployment of hydrogen pathways is a difficult decision-making challenge. Multi-Criteria Decision Analysis (MCDA) is tailored for addressing these difficulties, since it is made to evaluate diverse criteria such as, infrastructure costs, technology readiness, and regulatory compliance, which results in a fair and systematic decision-making.

In addition to that, route prioritization for hydrogen corridor deployment should consider quantitative factors, like costs and fuel demand, as well as qualitative aspects such as, stakeholders' concerns, infrastructure site locations, and social impact. Because of MCDA's expertise in combining quantitative and qualitative data, decision-makers are able to balance conflicting priorities from a variety of stakeholders, such as local communities, port authorities, and shipping companies within a route-based hydrogen corridor assessment. Successful project implementation and wider acceptance are facilitated by MCDA's transparency, which helps guarantee that decisions represent both short-term requirements and long-term sustainability. Broader policy frameworks, such as the Paris Agreement, EU ETS, and CBAM, may influence the overall decarbonization environment; however, in this study they are considered background policy drivers rather than direct route-level decision criteria.

Decision making methods: AHP and TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and the Analytic Hierarchy Process (AHP) were chosen due to their widespread use and complementary approaches in multi-criteria decision analysis. The AHP-TOPSIS framework is selected because it provides a user-friendly and transparent structure for evaluation. It is essential in optimal route selection for hydrogen-driven ships where judgement is often based on the primary source of data. The AHP MCDM method allows pairwise comparison with an integrated consistency check approach, which ensures the reliability of the judgement. This feature is not offered by many modern MCDM approaches, Furthermore, TOPSIS complements AHP by ranking alternatives on the basis of their closeness to positive ideal and negative ideal solution. This makes the approach well suited for problems with conflicting criteria such as efficiency, cost and emissions. Although new MCDM approaches like Best worst method (BWM) for weight determination and PROMETHEE for ranking offer improved consistency control,

they generally require larger samples of judgement, more demanding elicitation process and remain less familiar to hydrogen researcher and optimal route selection practitioner. Considering the study context, judgement data availability and the requirement for replicability and interpretability, the proposed AHP-TOPSIS framework offered a balanced, reliable and practically applicable methodology. Studies on sustainability and the energy transition have effectively used this integrated strategy, which provides an organized and transparent method for managing trade-offs across several competing criteria.

AHP (Analytic hierarchy process) The AHP is a systematic and well-structured methodology for decision-making[43]. Its ability to break down complex problems in a clear, systematic approach, incorporate both qualitative and quantitative criteria, and enable decision-makers to confirm judgment consistency makes it one of the most popular multi-criteria decision-making tools[44,45]. AHP enables decision-makers to decompose a complex problem into a hierarchical structure and derive relative priorities among alternatives in a logical and consistent manner[46,47]. The method was developed by Thomas L. Saaty, the AHP method is designed systematically in order to define and point out priorities in difficult decision-making topics. Organizing and analyzing complex decisions is simplified by dividing a problem into a hierarchy of smaller, easier-to-manage sub problems that may be assessed separately. By evaluating the relative importance of various criteria and sub-criteria using AHP's pairwise comparisons, decision-makers can develop priority scales based on stakeholders' opinions[43]. The Saaty's scale is shown in Table 8.

There are six phases in the Analytic Hierarchy Process (AHP):

1. Defining the problem, and the purpose of the decision: Clearly stating the problem and its relevant circumstances.
2. Identifying the criteria: Identifying the criteria and sub-criteria which may include substantial and insubstantial criteria.
3. Structuring of the Hierarchy: Putting the criteria in a hierarchical structure that shows how they relate to one another and how important they are.
4. Pairwise Comparisons: Comparing the criteria and assessing their relative importance through pairwise comparisons is an essential step in developing a priority ranking.
5. Balancing of decision: combining the results of the pairwise comparisons to produce a thorough rating of the criteria according to specified standards.
6. Evaluating Consistency: Assessing the pairwise comparisons' consistency to make that the conclusions obtained are reasonable and logical[50].

The working equations of this method is discussed in this section.

The experts are from academic backgrounds. This panel consisted of three members with relevantexpertise in hydrogen research and decision analysis: one university faculty member specializing in energy systems and sustainability assessment, one senior researcher from the hydrogen research sector and one researcher actively involved in hydrogen-related technological analysis. Individual pairwise comparison judgments obtained from the experts were aggregated using the Aggregation of Individual Judgments (AIJ) approach within the Analytic Hierarchy Process (AHP). Following the recommendation of Saaty, the geometric mean method is employed to combine the individual pairwise comparison values into a single group comparison matrix prior to deriving the priority weights. This approach preserves the reciprocal properties of the pairwise comparison matrix and is widely adopted in group AHP applications.

The pairwise comparison is crucial for developing hierarchical priority weight determination, which finally helps to rank the preferred alternatives. The pairwise comparison matrix structure can be represented as follows[51]:

$$C = \left(1 C_{12} C_{13} \ldots C_{1n} \frac{1}{C_{12}} 1 C_{23} \ldots C_{2n} \frac{1}{C_{13}} \frac{1}{C_{23}} 1 \ldots C_{3n} \ldots \ldots \ldots \frac{1}{C_{1n}} \frac{1}{C_{2n}} \frac{1}{C_{3n}} \ldots 1\right) \tag{13}$$

where each C_{ij} element represents the relative importance of ith alternative over jth alternative. If $C_{ij} = c$, then $C_{ji} = 1/c$. Moreover, for equal importance $C_{ij} = C_{ji} = 1$. Meanwhile, the diagonal elements are unity.

After constructing the pairwise matrix, normalizing the matrix is essential for standardizing the values for a consistent analysis. The normalized matrix (A) can be estimated by Eq. 14.

Description	Value
Equal importance	1
Equal to moderate importance	2
Moderately more important	3
Moderate to strong importance	4
Strongly more important	5
Strong to very strong importance	6
Very strongly important	7
Very strong to extreme importance	8
Extremely important	9

Table 8. Saaty scale for pairwise comparison matrix[46,48,49].

$$A = (a_{11}a_{12} \ldots \ldots a_{1n}a_{21}a_{22} \ldots \ldots a_{2n}a_{n1}a_{n2} \ldots \ldots a_{nn}) \tag{14}$$

where a_{ij} is defined as Eq. 15.

$$a_{ij} = \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}}, i = 1, 2, \ldots, n; j = 1,2, \ldots, n \tag{15}$$

The weights that represent the relative importance of each criterion are estimated for each alternative by averaging the values within each row of the normalized matrix. The weight of the criteria is determined by Eq. 16

$$w_i = \frac{1}{n}\sum_{j=1}^{n} a_{ij}, i = 1, 2, \ldots, n; j = 1,2, \ldots, n \tag{16}$$

In the next step, the logical consistency of judgements needs to be ensured. With the higher number of alternatives, the AHP processes become more sensitive to inconsistencies. To address this, the consistency ratio (CR) is determined to quantify the degree of consistency in the pairwise comparison. According to the AHP method, a CR is less than 0.1, confirming that the comparison matrix is sufficiently consistent for reliable results[52]. However, if the CR value exceeds the threshold value, indicates that the pairwise comparisons require reassessment to ensure consistency. The CR is determined by Eq. 17.

$$CR = \frac{CI}{RI} \tag{17}$$

where RI is the random index which is obtained from Table 9[46]. CI is the consistency index which is determined by Eq. 18.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{18}$$

where λ_{max} is the maximum eigenvalue of the matrix.

Technique for order preference by similarity to ideal solution (TOPSIS) This study employs the AHP-MCDM method to find the weights of the criteria through a pairwise comparison matrix. The matrix is developed through an expert's opinion. The study involved experts from the academics and from the hydrogen research sector. These derived weights of the criteria are then integrated into the TOPSIS process, as shown in Fig. 1[46,53]. The method was developed by Yoon and Hwang in the 1980s. This MCDM method serves as a complementary MCDM approach in an analytical framework[54]. This method operates on the optimal alternative selection principle based on proximity to ideal solutions. This method requires construction of a decision matrix (m X n) where m is the number of alternatives and n is the overall criteria.

The decision matrix is developed by Eq. 19[55].

$$D = (x_{11}x_{12}x_{13} \cdots x_{1n} \vdots \ddots \vdots x_{m1}x_{m2}x_{m3} \cdots x_{mn}), i = 1, 2, \ldots, m; j = 1,2, \ldots, n \tag{19}$$

Then the decision matrix is normalized. Every value for every criterion is normalized using the specified method by Eq. 20:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1, 2, \ldots, m; j = 1,2, \ldots, n \tag{20}$$

In the next step, the normalized matrix is then weighed using the predetermined criteria weights to develop the weighted normalized matrix. This is done by Eq. 21.

$$V_{ij} = r_{ij} X w_j \tag{21}$$

Next, for each criterion, the ideal best and the ideal worst solution is determined. The positive ideal solution is estimated by specific method, e.g., selecting the maximum values for benefit criteria and minimum values for cost criteria.

$$A^+ = \{V_1^+, \ldots, V_n^+\} \tag{22}$$

For maximization and minimization criteria, respectively, V_j^+ is given by Eqs. 23 and 24.

$$V_j^+ = (V_{ij}) \tag{23}$$

$$V_j^+ = (V_{ij}) \tag{24}$$

Criteria number	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 9. Random index (RI) values for different numbers of criteria in AHP.

Similar analysis is carried out for the negative ideal solution by Eq. 25.

$$A^{-} = \{V_1^{-}, \ldots, V_n^{-}\} \tag{25}$$

For maximization and minimization criteria, respectively, V_j^{+} is given by Eqs. 26 and 27.

$$V_j^{-} = (V_{ij}) \tag{26}$$

$$V_j^{-} = (V_{ij}) \tag{27}$$

After finding both positive and negative ideal solution the subsequent step involves the calculation of separation distance for each alternative to the ideal solution is estimated by Eqs. 28 and 29.

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^{+}\right)^2}, i = 1, 2, \ldots, m; j = 1,2, \ldots, n \tag{28}$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^{-}\right)^2}, i = 1, 2, \ldots, m; j = 1,2, \ldots, n \tag{29}$$

Finally, the closeness coefficient is determined for each alternative to the ideal solution by Eq. 30 [9].

$$C_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \tag{30}$$

Lastly the alternatives are ranked in descending order based on closeness coefficient value.

Working principle of AHP-TOPSIS decision making is shown in Fig. 4[46]:

Sensitivity analysis

The accuracy of the cost estimates under uncertainty in important input factors was evaluated by a sensitivity analysis. To assess how these modifications affect the relative cost comparison between diesel and hydrogen-powered routes, the price of hydrogen was changed by ± 50% and load factor assumptions were changed by ± 20%.

Base hydrogen price: 5.025 USD/kg.

Low hydrogen price (− 50%)

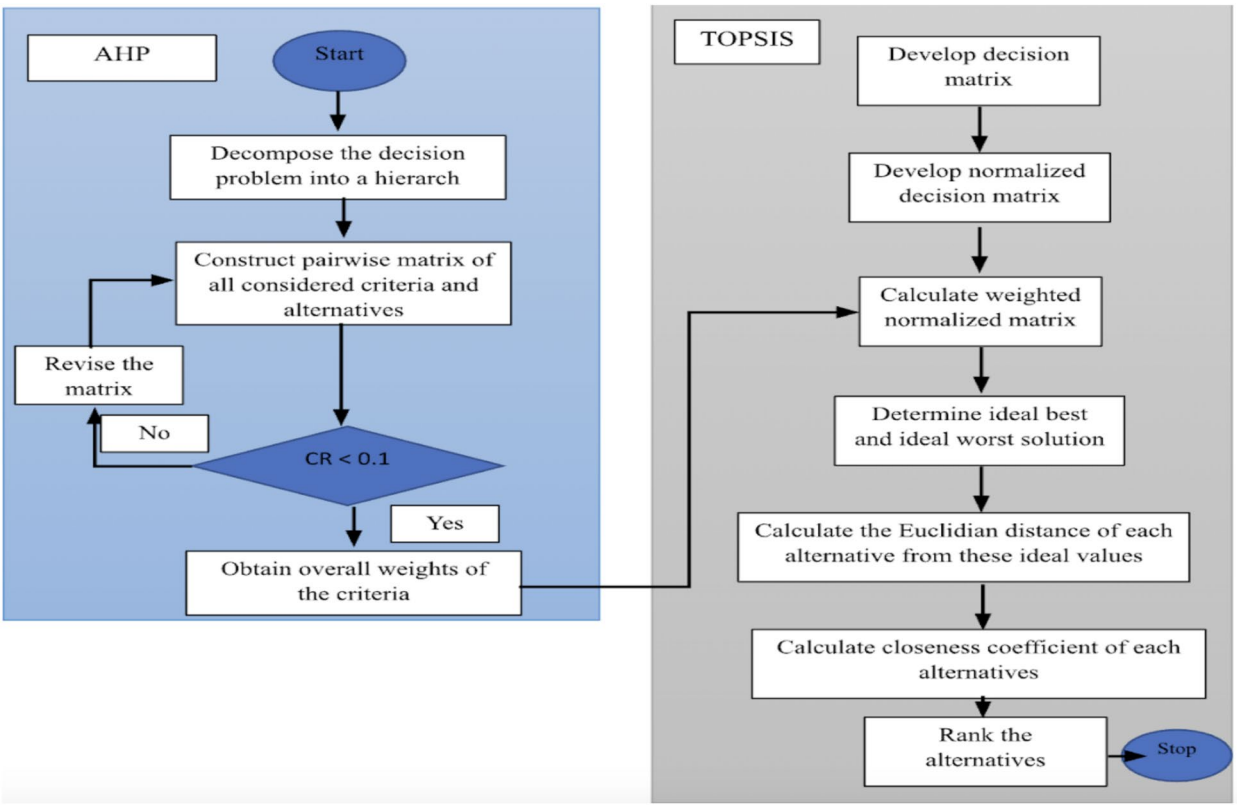


Fig. 4. Flowchart of AHP-TOPSIS decision making (Source: Ref.[46]).

$$5.025 \times 0.5 = 2.5125 \frac{USD}{kg} \tag{31}$$

High hydrogen price (+50%)

$$5.025 \times 1.5 = 7.5375 \frac{USD}{kg} \tag{32}$$

Assuming an engine load factor of 0.8, which corresponds to normal steady traveling circumstances, the baseline hydrogen demand was determined. The results have been evaluated for robustness by varying the load factor for hydrogen demand by ± 20% to account for possible changes in load circumstances, vessel speed, and operational efficiency.

H_2 cost low demand (-20% Load Factor)

Base load factor: 0.8 = 80%

$$-20\% = 0.8X0.2 = 0.16 \tag{33}$$

$$\begin{gathered} S_o 0.8 - 0.2 = 0.64 \\ S_o - 20\% \text{ Load Factor } = 64\% \\ \& \end{gathered}$$

$$+20\% = 0.8x1.2 = 0.96 \tag{34}$$

$$\text{So, } +20\% \text{ Load Factor } = 96\%$$

The variation is shown in Table 10.

In addition to the economic sensitivity analysis, the study further assessed the robustness and reliability of the estimated criteria weights by applying alternative objective-based MCDM approaches. Specifically, the CRITIC method was employed to derive weights based on the inherent contrast intensity and the degree of conflict among criteria. This method provides an objective weighting scheme by utilizing statistical properties of the data, thereby reducing subjectivity in the decision-making process. To complement this, an equal weightage approach was also considered, where all criteria were assigned identical importance. This served as a baseline scenario to evaluate how sensitive the results are to variations in the weighting structure. By comparing the outcomes obtained from these different weighting techniques, the study ensured that the final decision results are consistent and not overly dependent on a single weighting method. This comprehensive robustness check enhances the credibility and stability of the findings, demonstrating that the conclusions remain valid across different objective weighting frameworks. The details of the CRITIC method were discussed in[56].

Results

The study determines the best hydrogen refuelling infrastructure choices for maritime commerce, technical, operational, financial, and environmental criteria were used. AHP determines the criteria weights and the TOPSIS is primarily used to find the optimal solution.

Weight determination

To determine the criteria weights from the pairwise comparison matrix (shown in Table 11), the eigenvalue approach was used.

The weight of the cost-effectiveness, environmental impact, infrastructure accessibility, and energy consumption were calculated by using AHP and the result is shown in Table 12.

The consistency ratio (CR) of these weights is 0.081334 which satisfies the AHP criteria. The evaluations in AHP require logical coherency. Engine Number in Ship, Engine Power, Number of Stops per Trip, Hydrogen Demand per Trip, Site Selection, Nearest Hydrogen Infrastructure to Ports, CO_2 Emissions, and Hydrogen Trip Cost, are the criteria taken into consideration when evaluating hydrogen refueling infrastructure alternatives. Engine Number in Ship (0.228193) and Number of Stops per Trip (0.224194) are the most heavily weighted

Route number	Diesel cost (Base)	H_2 cost (Base)	H_2 cost low price (-50%)	H_2 cost high price (+50%)	H_2 cost low demand (-20%)	H_2 cost high demand (+20%)
Route 1	1,649,401.95	4,522,500	2,261,250	6,783,750	3,618,000	5,427,000
Route 2	1,530,527.05	4,200,900	2,100,450	6,301,350	3,360,720	5,041,080
Route 3	6,288,625.87	17,260,875	8,630,437.5	25,891,312.5	13,808,700	20,713,050
Route 4	6,879,604.09	18,878,925	9,439,462.5	28,318,387.5	15,103,140	22,654,710
Route 5	8,452,018.19	23,195,400	11,597,700	34,793,100	18,556,320	27,834,480
Route 6	5,464,639.07	14,999,625	7,499,812.5	22,499,437.5	11,999,700	17,999,550
Route 7	5,422,673.31	14,879,025	7,439,512.5	22,318,537.5	11,903,220	17,854,830
Route 8	3,813,700.80	10,462,050	5,231,025	15,693,075	8,369,640	12,554,460
Route 9	4,432,879.54	12,165,525	6,082,762.5	18,248,287.5	9,732,420	14,598,630
Route 10	5,698,268.33	15,637,800	7,818,900	23,456,700	12,510,240	18,765,360

Table 10. Sensitivity analysis of diesel and hydrogen trip costs across the maritime routes.

Criteria	Engine Number in Ship	Engine Power	Number of Stops per Trip	Hydrogen Demand per Trip	Site Selection	Nearest H2 Infrastructure to Ports	CO2 Emissions	H2 Trip Cost
Engine Number in Ship	1	2	2	2	2	4	5	2
Engine Power	0.5	1	2	2	2	2	5	2
Number of Stops per Trip	0.5	0.5	1	3	3	6	6	6
Hydrogen Demand per Trip	0.5	0.5	0.33333	1	2	3	3	2
Site Selection	0.5	0.5	0.33333	0.5	1	3	4	3
Nearest H2 Infrastructure to Ports	0.25	0.5	0.16667	0.33333	0.33333	1	3	2
CO2 Emissions	0.2	0.2	0.16667	0.33333	0.25	0.33333	1	2
H2 Trip Cost	0.5	0.5	0.16667	0.5	0.33333	0.5	0.5	1

Table 11. Pairwise comparison matrix.

Criteria	AHP
Engine Number in Ship	0.228193
Engine Power	0.180937
Number of Stops per Trip	0.224194
Hydrogen Demand per Trip	0.113415
Site Selection	0.105014
Nearest H2 Infrastructure to Ports	0.060477
CO2 Emissions	0.038657
H2 Trip Cost	0.049112

Table 12. Determined weights.

criteria, followed by Engine Power (0.180937) and Hydrogen Demand per Trip (0.113415). Site Selection and Nearest Hydrogen Infrastructure to Ports have weights of 0.105014 and 0.060477, respectively, whereas H2 Trip Cost has a weight of 0.049112. CO_2 Emissions (0.038657) is the least weighted criterion.These criteria represent operational and ship design characteristics, which are critical in determining logistical feasibility and hydrogen refuelling demand. Although cost and emission factors were considered, their weights were relatively lower, suggesting that operational requirements, ship characteristics, and infrastructure-related factors are more influential in the decision-making process.

Ranking analysis

The optimal result is evaluated by using the TOPSIS method and the result is shown in Table 13. The performance score is also shown in this table. The ideal and negative-ideal solutions were used to calculate each alternative's performance rank by Euclidean distances. The ideal positive and negative values are shown in Table 14.

The TOPSIS method uses the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS) to assess how close each alternative is to the ideal. PIS represents the most desirable value for each criterion, typically the maximum for benefit criteria, while NIS represents the least desired value. Distances to these ideal values are used as evaluation standards. Alternative 2, which received the highest total score (0.705600), was determined to be the best option for hydrogen refueling infrastructure based on the given criteria. Across all top-weighted criteria, it consistently scored better than the other routes, especially in terms of operational and energy-related factors. With strong feasibility, alternatives 10 (0.670441) and 1 (0.600235) came in close order. On the other hand, Alternative 6 received the lowest score (0.240017), showing poor performance in high-weight aspects including the number of refueling stops needed per trip and the demand for hydrogen. Comparably, Alternatives 7 and 5 performed badly, each receiving a score of 0.288759 and 0.296757respectively, indicating that they were unable to achieve important operational priorities. Overall, the findings show a distinct difference between the top-ranked alternatives, which are in line with operational efficiency, and the lower-ranked options, which are severely limited by logistical and technical factors.

Sensitivity analysis

Table 15 presents the sensitivity analysis results under variations in cost and demand parameters.

The sensitivity analysis results demonstrate a very high level of robustness in the ranking of alternatives, as no changes are observed across any of the examined scenarios, including + 50% cost increase, -50% cost decrease, + 20% demand increase, and -20% demand decrease. All alternatives retain their original positions under every variation, indicating that the decision-making model is highly insensitive to changes in the evaluated parameters.

In particular, Alternative 2 consistently remains the highest-ranked option in all scenarios, confirming its stability and superiority regardless of cost or demand fluctuations. Likewise, Alternatives 10, 1, 3, 8, 4, 9, 5, 7,

Alternative	Score	Rank
A1	0.600235	3
A2	0.705600	1
A3	0.592992	4
A4	0.330891	6
A5	0.296757	8
A6	0.240017	10
A7	0.288759	9
A8	0.532200	5
A9	0.308218	7
A10	0.670441	2

Table 13. TOPSIS performance scores and rankings.

Criteria	Positive Ideal (Vp)	Negative Ideal (Vn)
Engine Number in Ship	0.114097	0.038032
Engine Power	0.094537	0.031622
Number of Stops per Trip	0.020727	0.103634
Hydrogen Demand per Trip	0.010205	0.056356
Site Selection	0.045954	0.015318
Nearest H2 Infrastructure to Ports	0.000807	0.035041
CO2 Emissions	0.000874	0.024232
H2 Trip Cost	0.004415	0.024383

Table 14. Positive ideal solution (PIS) and negative ideal solution (NIS) values.

Alternative	Rank (Baseline)	Rank (+ 50% Cost increase)	Rank (-50% Cost decrease)	Rank (+ 20% Demand increase)	Rank (-20% Demand decrease)
Alternative 1	3	3	3	3	3
Alternative 2	1	1	1	1	1
Alternative 3	4	4	4	4	4
Alternative 4	6	6	6	6	6
Alternative 5	8	8	8	8	8
Alternative 6	10	10	10	10	10
Alternative 7	9	9	9	9	9
Alternative 8	5	5	5	5	5
Alternative 9	7	7	7	7	7
Alternative 10	2	2	2	2	2

Table 15. Sensitivity results with different cost and deman.

and 6 preserve their respective rankings throughout the analysis, demonstrating a strong resistance to parameter uncertainty.

The absence of any ranking shifts suggests that the relative performance differences among the alternatives are sufficiently significant to withstand substantial changes in the input conditions. This consistency indicates that neither cost variations nor demand fluctuations have a meaningful impact on the final decision outcome.

Overall, the sensitivity analysis confirms the robustness and reliability of the proposed decision-making framework. Since the rankings remain unchanged under all tested scenarios, the baseline results can be considered highly stable and dependable for decision-making purposes. Furthermore, the consistency of the rankings validates the credibility of the evaluation model and provides greater confidence in selecting Alternative 2 as the most suitable option).

The CRITIC-based weights show noticeable deviations from the baseline distribution, particularly by assigning higher importance to Engine Power (0.210745), Site Selection (0.162936), and CO_2 Emissions (0.101807) (Table 16). This indicates that, when objective data characteristics such as variability and inter-criteria conflict are considered, technical performance and environmental factors become more influential. In contrast, operational parameters such as Number of Stops per Trip and Hydrogen Demand per Trip receive relatively lower importance under CRITIC. The equal weighting method, on the other hand, eliminates any prioritization bias by assigning identical importance (0.125) to all criteria, providing a neutral benchmark for comparison.

Criteria	AHP (Baseline)	CRITIC	Equal
Engine Number in Ship	0.228193	0.133152	0.125000
Engine Power	0.180937	0.210745	0.125000
Number of Stops per Trip	0.224194	0.106196	0.125000
Hydrogen Demand per Trip	0.113415	0.099860	0.125000
Site Selection	0.105014	0.162936	0.125000
Nearest H2 Infrastructure to Ports	0.060477	0.081438	0.125000
CO2 Emissions	0.038657	0.101807	0.125000
H2 Trip Cost	0.049112	0.103865	0.125000

Table 16. Criteria weight from different methods.

Alternative	AHP	CRITIC	Equal
A1	3	4	2
A2	1	1	1
A3	4	3	4
A4	6	7	7
A5	8	9	9
A6	10	8	8
A7	9	10	10
A8	5	5	3
A9	7	6	6
A10	2	2	5

Table 17. Ranking under different weights.

The assessed ranking result is shown in Table 17.

Despite these differences in weight distribution, the ranking results remain largely stable. Alternative A2 consistently retains the top rank across all methods, confirming its robustness as the most preferred option.

Some moderate ranking variations are observed. For example, A1 shifts from 3rd position (baseline and equal) to 4th under CRITIC, while A3 improves from 4th to 3rd under CRITIC. These changes suggest that certain alternatives are sensitive to objective weighting, particularly when greater emphasis is placed on criteria with higher informational content.

At the lower end, alternatives such as A5, A6, and A7 consistently rank poorly, indicating that their relative performance is unaffected by changes in weighting schemes.

Overall, the sensitivity analysis confirms that although minor variations occur due to changes in weighting methodology, the overall ranking pattern remains consistent. This demonstrates that the decision-making framework is robust, and the final conclusions are reliable and not significantly influenced by the choice of weighting method.

Discussion

The predominance of operational and technical criteria in AHP assessment

The focus on technical and operational criteria in the AHP results highlights practical challenges that affect the design of hydrogen infrastructure. A decision-making environment that puts short-term profitability ahead of long-term sustainability is shown in the higher weighting of engine number, engine power, and number of stops per route over environmental or cost-related variables. This result emphasizes the study's importance by showing that, despite strong legislative and sustainability goals, real hydrogen adoption in maritime shipping will need overcoming short-term logistical and operational obstacles. This work provides useful insights that are frequently missed in port- or country-level evaluations by assessing viability at the route level, providing helpful recommendations for port authorities and infrastructure planners. This urgency is supported by recent research, which highlights that hydrogen-powered ships and shipping infrastructure are still in their development and face storage, safety, and regulatory alignment issues[22,57]. International evaluations also point out that although trade corridors and hydrogen projects are growing, infrastructure is still distributed unevenly among ports[18,58]. The importance of structured, multi-criteria approaches for balancing operational, economic, and environmental concerns is further confirmed by studies that use AHP–TOPSIS to hydrogen refueling infrastructure[59].All of these results highlight how crucial route-based, multi-criteria assessments like this one are to bringing sustainability goals and operational realities in the maritime industry into line.

Low weighting of CO_2 emissions and hydrogen fuel cost shows that environmental considerations are not yet dominant in early infrastructure planning, despite being key in frameworks like the Paris Agreement or CBAM. These results match previous studies[28] (Atilhan et al.2021) showing the gap between environmental policy goals and real maritime hydrogen adoption. Ship engine characteristics are crucial, proven by the high

scores given to engine-related criteria. Engine power and number affect hydrogen use, refuelling frequency, and integration. Similarly, the number of stops per trip impacts refuelling delays and infrastructure pressure. This reflects the operational impact a route has on infrastructure. Criteria were divided into technical and operational, environmental, economic, and safety-related categories. The distribution shows priority is given to immediate practical issues over long-term goals. Operational efficiency is favored over emissions or cost at this stage. This dominance also reflects a lack of financial responsibility alignment in current hydrogen transitions. In capital-intensive maritime infrastructure, decision-makers prefer low-risk factors like engine compatibility and route structure. Policy tools like regulations and subsidies are necessary to shift focus to emissions and lifecycle costs.

Genovese and Fragiacomo[25] highlight the need for safe, efficient hydrogen infrastructure. Technologies like compressors, storage tanks, and pipelines ensure quick refuelling and energy efficiency. Hydrogen's flammability makes safety systems like valves and sensors critical[60]. High-purity hydrogen[61] requires purification systems. Scalability depends on technical design[62]. Still, environmental and economic criteria had lower weights here, unlike Atilhan et al. (2021), who saw cost-effectiveness and GHG reduction as top adoption drivers. Di Lullo et al.[28] also emphasized economic feasibility and GHG emissions. This contrast shows a gap between operational needs and policy. In this study, engine power, port proximity, and fuel stop frequency outweighed emission and cost goals. Despite climate targets, maritime stakeholders focus on logistical feasibility. This suggests hydrogen success depends on matching current ship needs, not just sustainability.

Implications of route rankings for maritime hydrogen planning

The TOPSIS model, based on AHP-weighted criteria, ranked alternatives by proximity to the ideal solution. Route 2 scored highest (0.705600), due to its ideal number of stops, moderate hydrogen demand, and well-located infrastructure near ports. These factors reduce logistical difficulties and enhance operational efficiency, highlighting the importance of minimizing barriers like frequent refueling or poorly located ports in early hydrogen deployment. This outcome aligns with Smid et al.[20], who stress infrastructure location as key to hydrogen success. Li et al.[63] also support strategic station placement for efficient hydrogen use, noting that proximity to transport hubs like ports reduces costs and increases operational efficiency. Environmental and economic concerns like safety and land access and further support Route 2 as a strong candidate. Lower-ranked routes (below 0.57) may be feasible later but require significant upgrades or government incentives. The findings support gradual implementation, starting with technically feasible routes like Route 2. Route 2's performance confirms Van Hoecke et al.[23], who emphasize that strategically designed hydrogen networks simplify logistics and boost adoption, especially in high-volume corridors.

The study also compared CO_2 emissions from diesel ships and hydrogen pathways. Depending on the fundamental production and delivery conditions, the comparative analysis shows that hydrogen pathways have the potential to provide lower-emission maritime transportation. Under the simplified emissions framework adopted in this study, hydrogen pathways showed substantially lower emissions than conventional diesel pathways. These findings align with Mazloomi and Gomes[27], Kramer et al.[39], and Atilhan et al. (2021), who highlight hydrogen's emission reduction potential. Green hydrogen, especially when produced via electrolysis, offers near-zero emissions[62,64].

Policy recommendations for integrating hydrogen refueling infrastructure

In maritime shipping, hydrogen refueling infrastructure (HRI) requires supportive legislative frameworks in addition to operational and technological capability[64]. To help accelerate the adoption of hydrogen, this study and other recent research highlight the critical importance of strategic, financial, and legislative measures. One of the main suggestions is to use the trans-European transport network model to identify and rank high-potential ports according to traffic, logistics, and access to renewable energy in order to provide targeted regulatory and investment support[20]. Governments need to offer tax incentives and capital subsidies for hydrogen infrastructure (such as storage systems and electrolyzers), particularly in the early stages of adoption when expenses are high. To lower operating costs, other measures can include green port credits in line with FuelEU Maritime or changes to the carbon pricing system. Market transition would be supported and predictable demand would be ensured by gradual regulatory enforcement, such as combining requirements or renewable fuel limits[62].

Without significant regulatory pressure, market-driven adoption of hydrogen is unlikely given its existing cost disadvantage[21]. International cooperation is therefore crucial, and this includes standardizing fuel certification, refueling policies, and hydrogen supply chains across ports such as Rotterdam and Hamburg[20]. Furthermore, strong technical rules should require criteria for safety, hydrogen purity, and equipment compatibility[22]. To guarantee safe, efficient HRI operation, workforce training programs for engineers, ship crews, and port employees are equally important.

However, there are some limitations to this work. Although the research primarily takes a techno-economic and policy-oriented approach, real-world implementation also depends on stakeholder willingness, geopolitical dynamics, and unpredictable technical advancements. Additionally, although the report identifies important institutional measurements, it does not adequately quantify the impact of each barrier on adoption, including supply chain immaturity, regulatory uncertainty, and high capital expenditures. To close this gap, obstacle degree analysis could be used in future studies to determine the relative importance of various difficulties. With a better knowledge of the obstacles that most restrict the adoption of hydrogen, policymakers and industry stakeholders would be better able to prioritize actions.

Together, these institutional measures provide the policy foundation required to carry out the hydrogen infrastructure roadmap, despite certain constraints and challenges. Without them, the technical and logistical insights from this study will remain difficult to scale.

Conclusion and future suggestions

Ten international shipping routes between Türkiye and Hamburg were examined using the AHP–TOPSIS framework in this study, which found that operational and technical viability were considerably more important than cost or environmental considerations. The fact that criteria like engine number (0.228193) and engine power (0.180937) were more important than CO_2 emissions (0.038657) and hydrogen trip cost (0.049112) indicates that decision-making prioritizes operational feasibility. Alternative 2 received the highest TOPSIS score of 0.705600 out of all the routes, followed by Alternatives 10 (0.670441) and 1 (0.600235) Alternative 6 had the lowest score of 0.257970. The sensitivity analysis results also validated the outcome of this work.

These results demonstrate a significant gap between practical priorities and climate goals. Sustainability will continue to be sacrificed to practical feasibility in the absence of more robust legislative incentives. In addition to direct maritime policies like IMO carbon pricing, more general policy mechanisms like CBAM may have an impact on priorities, but differences between regions must be acknowledged: Early pilots are most suited for ports in Northern Europe, whereas bilateral cooperation and phased investment are needed in Türkiye. However, rather than conducting a full lifecycle assessment, this study applies a simplified comparative emissions framework intended for strategic route prioritization. The environmental assessment is designed to support relative route comparison within the MCDA framework and should not be interpreted as a comprehensive lifecycle emissions analysis. Under the assumptions adopted in this framework, hydrogen pathways were associated with lower estimated emissions than conventional diesel operation, indicating their potential contribution to maritime decarbonization. Overall, hydrogen shows technical feasibility as a marine fuel on selected routes; however, wider adoption will require coordinated infrastructure development, policy support, and stakeholder engagement.

Data availability

Data will be provided upon request.

Code availability

The MATLAB scripts used to implement the AHP, TOPSIS, and CRITIC calculations and the associated sensitivity analyses are attached as a *Supplementary file*. The code implements established MCDA methods for reproducibility of the analyses reported in this study; no new computational algorithm or software tool is introduced.

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Author contributions

MEJ completed the data collection, analysis, figure preparations and writing the initial manuscript, SD guided the AHP-TOPSIS procedure and provided the code for MATLAB, reviewed the manuscript and MG reviewed, edited and finalized the manuscript.

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Competing interests

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