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Environmental and Cost Assessments of Marine Alternative Fuels for Fully Autonomous Short-Sea Shipping Vessels Based on the Global Warming Potential Approach

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Abstract: This research paper presents an effective approach to reducing marine pollution and costs by determining the optimal marine alternative fuels framework for short-sea shipping vessels, with a focus on energy efficiency. Employing mathematical models in a Python environment, the analyses are tailored specifically for conventional and fully autonomous high-speed passenger ferries (HSPFs) and tugboats, utilizing bottom-up methodologies, ship operating phases, and the global warming potential approach. The study aims to identify the optimal marine fuel that offers the highest Net Present Value (NPV) and minimal emissions, aligning with International Maritime Organization (IMO) regulations and environmental objectives. Data from the ship's Automatic Identification System (AIS), along with specifications and port information, were integrated to assess power, energy, and fuel consumption, incorporating parameters of proposed marine alternative fuels. This study examines key performance indicators (KPIs) for marine alternative fuels used in both conventional and autonomous vessels, specifically analyzing total mass emission rate (TMER), total global warming potential (TGWP), total environmental impact (TEI), total environmental damage cost (TEDC), and NPV. The results show that hydrogen (H2-Ren, H2-F) fuels and electric options produce zero emissions, while traditional fuels like HFO and MDO exhibit the highest TMER. Sensitivity and stochastic analyses identify critical input variables affecting NPV, such as fuel costs, emission costs, and vessel speed. Findings indicate that LNG consistently yields the highest NPV, particularly for autonomous vessels, suggesting economic advantages and reduced emissions. These insights are crucial for optimizing fuel selection and operational strategies in marine transportation and offer valuable guidance for decision-making and investment in the marine sector, ensuring regulatory compliance and environmental sustainability.

Keywords: conventional; fully autonomous; tugboat; high-speed passenger ferry; alternative fuels; NPV; IMO; AIS; global warming potential approach; KPIs

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1. Introduction

The shipping industry, responsible for transporting over 80% of international trade, is the most energy-efficient mode of goods transport. However, despite the relatively low total carbon dioxide (CO_2) emissions from shipping, the industry cannot ignore its role in global warming. The fourth International Maritime Organization (IMO) GHG report indicates that shipping emitted approximately 1056 million tonnes of CO_2 in 2018, accounting for 2.89% of global CO_2 emissions [1]. Ship energy management significantly influences both cost efficiency and environmental impact, primarily due to the considerable CO_2 emissions stemming from ship operations. Decreasing energy consumption not only directly mitigates emissions, but also reduces the environmental footprint and operational expenditures [2]. Therefore, the IMO has endorsed a proposed amendment requiring the adoption of a Ship Energy Efficiency Management Plan (SEEMP) and an Energy Efficiency

Design Index (EEDI) for newly constructed vessels. This regulatory measure aims to curtail greenhouse gas (GHG) emissions within the maritime domain [3]. The proposed net zero target for 2050 by the IMO [4] can be achieved through the changes in ship design, including weight reduction, the use of advanced coatings on the hull [5], and the optimization of the ship's hull dimensions and bow thrusters, just to mention a few [6]. Similarly, energy efficiency and sustainability can be achieved by using alternative fuels with minimal or zero emissions onboard vessels. The best marine alternative fuels are biofuels (biodiesel, biomethane, bioethanol), E-fuels (green hydrogen, E-diesel, green ammonia, E-methane), blue fuels (blue hydrogen, blue ammonia), electricity (grid, renewable energy sources), and fossil fuels (a mixture of fossil fuel and advanced biofuels) [7]. However, the application of some of the aforementioned alternative fuels is not mature in terms of production processes and bunkering infrastructure [6,8]. The choice of energy source or fuel type for a vessel [9] is contingent upon both the vessel's classification and the specific route it navigates on [10,11].

Short-sea shipping vessels [12] facilitate the transportation of goods and passengers over relatively short distances [11] within port waters and between deep sea terminals [13]. As evidenced in Europe and other North American regions [14,15], short-sea shipping presents opportunities to improve efficiency and address environmental impacts associated with goods and passenger transport [16]. Moreover, short-sea shipping vessels operating in inland waterways play a pivotal role in regional and national transportation networks, offering benefits such as reduced energy consumption, lower emissions, and maintaining a high safety standard compared to road transport [17–19].

The International Convention for the Prevention of Pollution from Ships (MARPOL) mandates four key requirements for both new and existing vessels to address air pollution, emphasizing cleaner fuels, renewable energies, emission reduction technologies, and enhanced energy efficiency [9,20]. The utilization of maritime autonomous surface ships (MASS) offers a promising approach to mitigate environmental impact within the maritime sector, operating independently with artificial intelligence (AI)-driven navigation. Fully autonomous fleets, without onboard crews, demonstrate a significant conservation of energy and a reduction in pollution [21], with a notable decrease of 74.5% [22] in energy consumption in autonomous container vessels compared to traditional counterparts [23]. Integrating MASS with marine alternative fuels emerges as a robust strategy for reducing GHG emissions in maritime operations [24,25].

In the quest to identify the most suitable alternative fuel for vessels, two principal methodologies are used to measure ship fuel consumption and predict emissions: the top-down and bottom-up approaches [26]. The top-down approach, used in several existing studies, focuses on the utilization and analysis of marine fuel sales data [27,28]. Conversely, an increasing number of studies are adopting the bottom-up approach [26,27,29], which involves analyzing fuel consumption in relation to specific shipping activities [30]. The latter method offers a more accurate representation of actual emission levels. To predict fuel usage in maritime vessels, the bottom-up methodology uses a cubic correlation between fuel consumption and vessel speed [27]. Table 1 presents comparative analyses conducted by previous researchers that were aimed at identifying the optimal marine fuel.

A recent review by Chen and Yang [31] explored the application of automatic identification system (AIS)-based methods for estimating ship emissions. This study encompassed data acquisition via AIS, the analysis of ship characteristics, the calculation of engine loads, and the determination of emission factors. In contrast, Aarskog et al. [32] evaluated the economic feasibility of fuel cell (FC) propulsion for high-speed crafts (HSC) using an energy analysis method, juxtaposing it with traditional diesel and biodiesel alternatives. Their findings indicate a potential cost competitiveness of FC-equipped HSCs compared to diesel propulsion by 2025–2030. Similarly, Jafarzadeh and Schjølberg [33] used the cubic law of design and operational speed to examine optimal propulsion power utilization for enhancing electric or hybrid propulsion in suitable ship types. Ocean-going reefers achieve peak efficiency at 0.6–0.7 of their capacity loads, whereas other vessels peak at lower loads, limiting hybrid or electric integration benefits. Additionally, various studies [34–39] have investigated the economic and emissions impacts of alternative marine fuels based on ship-specific considerations. These studies hinge on intricate technical specifications and operational data that are distinct to individual vessels. For instance, Kouzelis et al. [34] applied simple multi-attribute rating technique (SMART) decision-making models to assess optimal alternative fuel technologies for large container vessels, highlighting upgraded bio-oil (UBO), Fischer–Tropsch diesel (FTD), and liquefied biomethane (LBM) as promising future fuels. Meanwhile, conventional fuels like heavy fuel oil (HFO) and liquefied natural gas (LNG) are likely to maintain dominance without regulatory changes. Additionally, Kosmas and Acciaro [35] used the Cobweb Theorem to analyze the economic and environmental effects of bunker levies on shipping fuels for cargo ships, showing potential reductions in speed and fuel consumption, akin to sector energy efficiency improvements through regulatory measures. Similarly, Ammar and Seddiek [36] explored selective catalytic reduction (SCR), seawater scrubbers (SWS), marine gas oil (MGO), and LNG using eco-environmental analysis methods for reducing RoRo exhaust emissions, with LNG emerging as the most effective option both economically and environmentally. Furthermore, Helgason et al. [37] compared conventional methanol with natural gas (NG) and renewable methanol (RN) with HFO using impact pathway analysis (IPA) in Iceland's maritime sector, highlighting fossil methanol's current cost competitiveness and projecting renewable methanol's future cost-effectiveness. On the contrary, there is limited literature addressing simultaneous economic and emission analyses for both conventional and autonomous MASS [38,39]. For example, Jovanović et al. [38] used cubic law of design to conduct environmental and economic evaluations of RoRo passenger ferries, identifying methanol and electric propulsion as optimal choices across all routes. Autonomous shipping shows substantial ecological and economic benefits across various propulsion options and vessel types, except for renewable hydrogen-powered vessels on longer shipping routes. Similarly, Kretschmann et al. [39] used cost–benefit analysis to perform a comprehensive cost analysis comparing conventional and autonomous bulkers, emphasizing the economic advantages of autonomous vessels, particularly with MDO despite higher voyage expenses.

The complexities inherent in integrating alternative fuels into maritime operations underscore the necessity for tailored solutions that consider vessel type and operational context. However, further advancements are required in several key areas. Notably, there remains a gap in comprehensive studies that compare the environmental and economic impacts of marine alternative fuels across both conventional and autonomous vessels using AIS data and employing a global warming potential approach. Previous studies conducted by authors [32,33] focused solely on conventional vessels using AIS data. The sensitivity analysis performed by Aarskog et al. [32] was restricted to fuel cells without the consideration of other fuel types and lacked a stochastic analysis. Additionally, Jafarzadeh and Schjølberg [33] exclusively calculated power consumption for main engines, neglecting the significant contributions of auxiliary engines. Furthermore, analyses conducted by some authors [38,39] utilized ship-specific particulars rather than AIS-based methods, limiting their ability to capture real-time operational dynamics effectively. Moreover, previous assessments often omitted critical factors such as carbon monoxide emissions, port costs, and hydrogen storage tank costs [38,39]. Furthermore, the environmental impacts, environmental cost assessments, and stochastic analysis were frequently overlooked across studies. Neglecting these aspects can lead to inaccurate estimations of a fuel's ecological footprint and economic implications, thereby hindering informed decision-making regarding sustainable fuel selection. Incorporating comprehensive environmental and economic analyses, including stochastic considerations, is essential for ensuring robust evaluations of marine alternative fuels. Such an approach facilitates more informed decisions that balance environmental sustainability with economic viability, crucial for advancing the adoption of sustainable marine fuels. For instance, Table 1 provides a comparative analysis of research utilizing a bottom-up methodology, which integrates AIS data and ship particulars to evaluate the environmental and economic impacts of alternative fuels in marine applications.

Table 1. Comparative analysis of environmental and economic assessments for marine alternative fuels.

Objective	Study Area	Type of Ship	Type of Fuel Analysis	Data Source	Comments	Reference
Perform economic assessments contrasting fuel cell with diesel and biodiesel	Norway	HSC	Hydrogen, diesel, and biodiesel	AIS Data	No stochastic analysis was performed, only sensitivity analysis on hydrogen FC.	[32]
Analyze operational profiles to select suitable ships for electric/hybrid propulsion	Norway	Tankers, bulk carriers, general cargo ships, container ships, roll-on/roll-off (Ro-Ro) ships, reefers (refrigerator/freezer), offshore ships, and passenger ships.	FC, batteries, and MGO	AIS Data	No sensitivity or stochastic analysis was performed.	[33]
Optimize fuel technology for efficient freight across technical and environmental standards	Denmark to Greece from Denmark, China, Norway, Greece	Large container vessel	HFO, FTD, UBO, and LBM	Ship particulars	Conducted sensitivity analysis on SFOC [2], fuel cost, and vessel speed relative to required freight rate (RFR).	[34]
MBMs [3] proposals improve shipping sector efficiency and reduce emissions	N/A	Cargo ships	N/A	Ship particulars	No sensitivity, environmental, or stochastic analysis was conducted.	[35]
Analyze environmental and economic impacts of diverse ship fuel options for IMO compliance	Hurghada port (Egypt) and Duba port (Saudi Arabia)	Medium RoRo cargo ship	SCR, SWS, MGO, and LNG	Ship particulars	Sensitivity analysis is conducted based on variable emission reduction percent and interest rate.	[36]
Conducts comprehensive cost-competitive analysis of three marine fuels.	Iceland	N/A	NG, RN, and HFO	N/A	Performed sensitivity analysis on years, price trajectories, and total costs; no stochastic analysis conducted.	[37]
Optimizing power for autonomous RoRo ships considering environmental and economic factors	Croatia	RoRo passenger ship [1]	MDO, HFO, LNG, methanol, electricity, and hydrogen	Ship particulars	Sensitivity analysis focused on autonomous vessels' economic input variations only; stochastic analysis excluded for optimal fuel.	[38]
Examines autonomous bulker costs vis-à-vis conventional vessel	Australia to Europe	Bulk carrier [1]	MDO and HFO	Ship particulars	Sensitivity analysis on RFR impact, emphasizing fuel consumption and vessel costs; no stochastic analysis.	[39]

[1]. Both conventional and autonomous vessels are considered. [2]. SFOC: specific fuel oil consumption [3]. MBMs: market-based measures.

Despite considerable existing literature on alternative marine fuels, consensus remains elusive regarding the optimal choice for future maritime operations. Moreover, few studies have comprehensively addressed the environmental impacts and simultaneous variations in input parameters, particularly concerning the application of marine alternative fuels across diverse short-sea vessels with varying speeds and routes. Incorporating dynamic methodologies within bottom-up calculations of ship pollutant emissions using geospatial inputs provides a precise depiction of real-time fuel consumption and emission dispersion during vessel operations. Such insights are crucial for stakeholders aiming to integrate alternative fuels effectively within the marine sector. Therefore, this research aims to investigate how these alternative fuels could potentially influence the design and operation of both conventional and autonomous surface ships.

This study seeks to forecast fuel consumption for conventional and fully autonomous high-speed short-sea shipping vessels based on their operational profiles using AIS data, employing a bottom-up approach. Furthermore, it evaluates the environmental impact and associated costs of these alternative marine fuels. The modeling considers key performance indicators (KPIs) and utilizes annual AIS data alongside ship specifications and port data. Predictions of fuel consumption are made using different marine fuels, employing a global warming potential approach in conjunction with design specifications and operational speeds. Additionally, the study assesses emission factors to determine environmental impacts and cost implications, integrating cost metrics for a comprehensive economic analysis. Sensitivity analyses are performed to evaluate the impact of variable inputs on the models, aiming to identify optimal marine alternative fuels that not only comply with environmental policies but also offer high profitability.

This research makes significant contributions to the existing literature by introducing a novel application of the global warming potential approach tailored specifically for conventional and autonomous ships. This approach facilitates the assessment of mass emission rates, global warming potential, environmental impact, real-time fuel consumption, and associated costs for proposed alternative fuels. Moreover, the study introduces sensitivity and stochastic analyses that explore the effects of varying load factors, vessel speeds, emissions, and nautical miles on the selection of optimal marine alternative fuels. The prior literature has typically overlooked such detailed sensitivity analyses. Additionally, this research leverages port data from Los Angeles and Long Beach to develop a comprehensive mathematical model for environmental-economic assessments specific to the chosen vessels. This model serves as a valuable tool for marine stakeholders to evaluate emission policies and identify feasible marine fuels that offer both environmental benefits and economic viability for short-sea shipping operations.

The rest of the paper is organized as follows: Section 2 introduces the materials and methods, which include data collection and the features for evaluating fuel consumption; environmental and cost analyses for the proposed marine alternative fuels are also detailed. The results and a discussion are presented in Sections 3 and 4, respectively. Section 5 provides concluding remarks as well as perspectives on potential future research directions.

2. Materials and Methods

The ship's AIS data, specifications, and port information are employed to determine power, energy, and fuel consumption. Additionally, the parameters of the proposed marine alternative fuels are integrated with these data for environmental and cost analyses using the global warming potential approach, with the aim of identifying KPIs. Sensitivity analyses are conducted for each alternative fuel across both conventional and autonomous vessels to validate their test results. Furthermore, a stochastic analysis is specifically conducted on the optimal alternative marine fuel for the chosen vessel. Figure 1 depicts the analysis flowchart. All computations are performed in a Python 3.11.6 environment, with comprehensive explanations and relevant equations presented in subsequent sections. This framework is specifically designed to evaluate fuel consumption and emissions based on ship AIS data and particulars.

The program begins by importing essential libraries, including Pandas for data manipulation, NumPy for numerical calculations, Matplotlib and Seaborn for visualizing fuel consumption, emissions, KPIs, and NPV, as well as Statsmodels for advanced statistical modeling and SciPy for statistical analysis and distributions.

Initially, the AIS dataset is loaded, and critical parameters such as ship particulars, engine power, fuel properties, and emission factors (as outlined in tables in Section 2.4), along with financial data, are defined. The data undergo preprocessing to ensure they are clean and properly formatted, addressing any missing values and converting units as required.

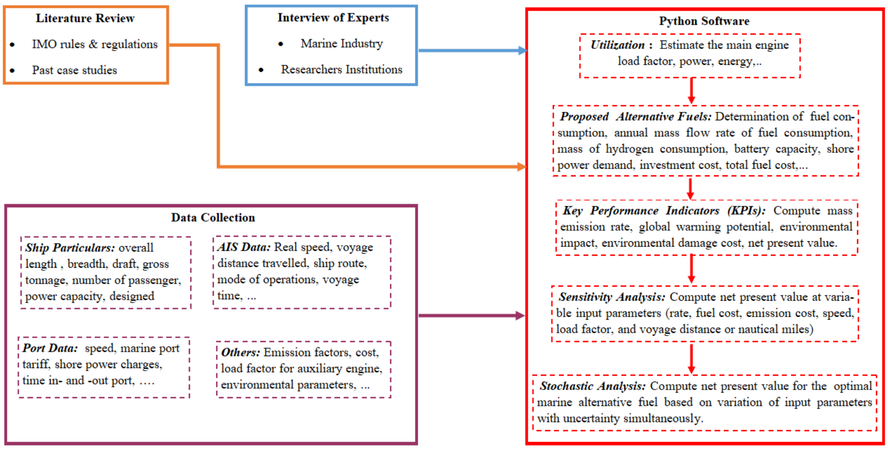


Figure 1. Flowchart of the data analysis process for marine alternative fuels in conventional and fully autonomous vessels.

The core of the code includes functions that calculate fuel consumption based on ship speed and engine power, estimate emissions based on the fuel consumed, and compute key performance indicators to offer insights into fuel efficiency and operational costs. Additionally, NPV is calculated to assess the financial viability of the vessel's operations over its service life.

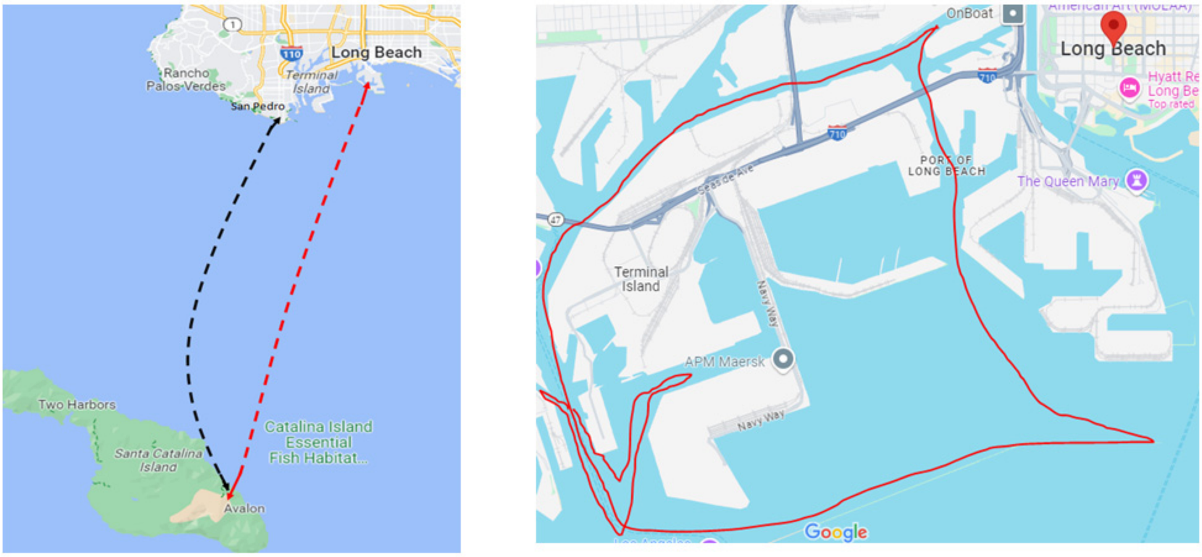
Furthermore, the code incorporates sensitivity and stochastic analyses to evaluate how variability in key parameters—such as fuel cost, distance, speed, emission cost, load factor, and rate—affects the NPV results for fully autonomous vessels. The stochastic analyses model uncertainty in these key parameters concerning the NPV. The findings are visualized through various plots, illustrating trends in fuel consumption, emissions, NPV, and KPIs over the vessel's service life.

2.1. Ship Main Particulars and Navigation Route

For this research, we have selected a high-speed passenger ferry (HSPF) and a tugboat as the vessels under study. Ship specifications for these two vessels are sourced from various entities including the MarineTraffic [40], shipbuilders, fleet operators, and port, and they are presented in Table 2. Similarly, details regarding operating modes and coverage are extracted from automatic identification system (AIS) data obtained from MarineTraffic. According to the AIS data, the high-speed passenger ferry (HSPF) shuttles passengers and goods between the mainland (specifically the Port of Los Angeles and the Port of Long Beach) and Santa Catalina Island (Avalon). Additionally, the tugboat operates within the ports of Los Angeles and towing vessels from the Port of Los Angeles to either the Port of Long Beach or Seal Beach. A segment of the navigation routes is illustrated in Figure 2.

Table 2. Main particulars for the conventional vessels [40].

Parameters	Vessel 1	Vessel 2
Ship Type	HSPF	Tugboat
Overall Length (m)	44.20	25
Breadth (m)	10.45	10
Draft (m)	3.96	5
Gross Tonnage (ton)	462	298
Design Speed (knots)	37	12.5
Number of Passenger,	381	2–6
Main Engine Power(kW)	6869.56	3840.35
Aux Engine Power (kW)	198	250
Navigation Route(s)	Avalon—Long Beach Avalon—Los Angeles	Los Angeles—Long Beach Los Angeles—Seal Beach



(a) (b)

Figure 2. A segment of navigation routes depicted on a map sourced from Google Maps [41]: (**a**) HSPF, (**b**) tugboat.

2.2. *Estimation of Fuel Consumption*

Fuel consumption in vessels occurs during propulsion and while powering auxiliary systems onboard. Therefore, to accurately assess total fuel consumption per voyage, it is essential to consider factors such as ship speed, load factor, and power demand along navigation routes.

2.2.1. Ship Speed

The speed of a vessel is directly correlated with its fuel consumption. As a result, the operational pattern of the vessel along navigation routes is segmented into three distinct phases based on speed and engine load: cruising mode, maneuvering mode, and idling (or hoteling) mode. In cruise mode, operational activities are governed by the inputs of cruise distance and speed. Typically, for conventional vessels, the cruising speed ($V_{crus,conv}$) exceeds 12 knots for normal cruising and falls within the range of 8 knots to 12 knots for low cruising speed. In maneuvering mode, the vessel's speed is determined based on the nautical distance from land or to the port (that is, from the port entrance to the berth, pier, wharf, or dock). For instance, at ports like the Port of Los Angeles (San Pedro) and Port of Long Beach, maneuvering operations occur within the precautionary area, limiting the maneuvering speed for conventional vessels ($V_{man,conv}$) to less than 12 knots [42,43].

In the case of idle mode, when the ship is at berth or anchorage, the main engines are shut off, resulting in a speed of zero ($V_{idle,conv}$), while the auxiliary engines continue to operate. Table 3 presents the estimated average speeds for the vessels using real-time data for the three operational modes based on AIS data.

Table 3. Average daily estimates for marine vessels across two operational modes.

Type of Vessel	Average Cruising (Knots)	Average Maneuvering (Knots)
HSPF	23.70	10.25
Tugboat	9.50	6.70

2.2.2. Load Factor (LF)

The load factor represents the percentage of the vessel's total power. Utilizing AIS data for the vessels, the estimation of the load factor for the main engines ($LF_{ME,i}$) is derived. Hence, by employing the Propeller Law, the $LF_{ME,i}$ is determined as follows [44,45]:

$$LF_{ME,i} = \left(\frac{V_{avg,conv,i}}{V_{max}}\right)^3 = \left(\frac{V_{avg,conv,i}}{\left(\frac{V_{design}}{0.937}\right)}\right)^3 \tag{1}$$

where $LF_{ME,i}$ is the load factor for the main engine, i represents the vessel operating modes (that is, cruising, maneuvering, and idling), $V_{avg,conv,i}$ is the average speed for the operational modes in Table 3 (knots), V_{max} is the maximum speed (knots), V_{design} is the design speed (knots), and 0.937 represents a safety margin that offers a conservative estimate for maximum speed, ensuring that the vessel can operate effectively under various conditions while minimizing the risk of damage or excessive strain on the propulsion system. In addition, if the determined $LF_{ME,i}$ is less than 2%, it is adjusted to a minimum of 2% [44]; this is to ensure a baseline level of efficiency and to maintain consistency in performance metrics.

The same activity-based calculation formula was applied to the auxiliary engine. However, since these engines are primarily used for providing electricity rather than propulsion, their loads are independent from the vessel speed. In addition, given the limited data available regarding onboard auxiliary engines, the load factors ($LF_{Aux,i}$) were derived from a technical report conducted by the US Environmental Protection Agency for the ports of Los Angeles and Long Beach [44,46]. Table 4 presents the estimated load factors for both main engines and auxiliary engines.

Table 4. Estimated load factors of the main engines and auxiliary engines for the vessels.

Engine Type	Type of Ships	Cruising	Maneuvering	Idling
Main Engines	HSPF	21.82%	2.00% [1]	-
	Tugboat	26.10%	3.87%	-
Aux Engines	HSPF	17%	45%	22%
	Tugboat	17%	45%	22%

[1]. The determined value is 1.76%, but it has been adjusted to 2% for the purpose of this research.

2.2.3. Ship Power Demand and Energy Consumption

The load demand varies for each mode of operation and is specific to each vessel. Consequently, the power requirements for the vessel and its integrated auxiliary systems are met by the onboard main engines and auxiliary engines. To illustrate this, the effective power generated by the main engines for propelling the conventional ship ($P_{eff,ME-conv}$) is calculated as follows:

$$P_{eff,ME-conv} = P_{nom-ME,conv}\ \eta_{ME}\ LF_{ME,i} \tag{2}$$

where $P_{nom-ME,conv}$ is the total nominal power of the main engine (kW), η_{ME} denotes the efficiency of the main engines which falls within the range of 70–90% [47], and V_{design} is the ship design speed (knots). Table 4 shows the different load factors.

Likewise, while the vessel is in port during idling mode, the auxiliary engines are operational, and the resultant effective power generated by the installed auxiliary engines on the conventional vessel ($P_{eff,Aux-conv}$) at an efficiency (η_{Aux}) of 95% [48] is represented as follows:

$$P_{eff,Aux-conv} = P_{nom-Aux,conv}\ \eta_{Aux}\ LF_{Aux,i} \tag{3}$$

Hence, the total power required ($P_{total-conv}$) for the conventional ship, considering all three modes of operation, is calculated as follows:

$$P_{cru-conv} = P_{nom-ME,conv}\,\eta_{ME}\,LF_{ME,cru} + P_{nom-Aux,conv}\,\eta_{Aux}\,LF_{Aux,cru} \tag{4}$$

$$P_{man-conv} = P_{nom-ME,conv}\,\eta_{ME}\,LF_{ME,man} + P_{nom-Aux,conv}\,\eta_{Aux}\,LF_{Aux,man} \tag{5}$$

$$P_{idle-conv} = P_{nom-Aux,conv}\,\eta_{Aux}\,LF_{Aux,idle} \tag{6}$$

$$P_{total-conv} = P_{cru-conv} + P_{man-conv} + P_{idle-conv} \tag{7}$$

where $P_{cru-conv}$ is the cruising power for the conventional ship (kW), $LF_{ME,cru}$ and $LF_{Aux,cru}$ are the load factors for main and auxiliary engine at cruising state (%), $P_{man-conv}$ is the maneuvering power for the conventional ship (kW), $LF_{ME,man}$ and $LF_{Aux,man}$ are the load factor for the main and auxiliary engines at maneuvering state (%), $P_{idle-conv}$ is the idle power for conventional ship (kW), and $LF_{Aux,idle}$ is the load factor of auxiliary engine at idle state.

Similarly, the total energy consumption by the conventional vessel ($E_{total-conv}$) in kilowatt-hours (kWh) is estimated based on the ship's load and speed. Thus, the relationship between loads and the three states of operation in real-time is expressed as follows:

$$E_{total-conv} = \left(P_{idle-conv}\,T_{idle,conv}\right) + P_{man-conv}\left(\frac{ND_{man,conv}}{V_{man,conv}}\right) + P_{cru-conv}\left(\frac{ND_{crus,conv}}{V_{crus,conv}}\right) \tag{8}$$

where $V_{crus,conv}$ denotes the instantaneous cruising speed for the conventional ferry (knots), $ND_{man,conv}$ is the nautical distance from berth during maneuvering phase (NM), $ND_{crus,conv}$ denotes the length of navigation route per one-way trip during cruising (NM), and $V_{man,conv}$ represents the instantaneous maneuvering speed for the conventional vessel (knots).

In the case of fully autonomous ships, we assume that they share the same dimensions and navigation routes as conventional ships to prevent excessive fuel consumption. Moreover, the absence of a ship crew results in a reduction in the required auxiliary power [49], as well as the elimination of crew living quarters and certain applicable auxiliary systems, which affects the vessel's displacement and decreases the space consumption [50] and required propulsion power [22]. For instance, studies have shown that a fully autonomous container vessel can achieve energy savings of up to 74.5% compared to a conventional one, primarily due to the elimination of facilities and equipment used by sailors [22]. The vessels utilized in our research are short-sea vessels, which return to port after each trip, as opposed to container ships that undertake long voyages. However, the assumptions in this study are derived from findings concerning fully autonomous container vessels, owing to the limited data available on energy consumption for fully autonomous tugboats and high-speed ferries. However, in our research, although there is no ship crew, passengers are still onboard. Therefore, we assume that the total power required by autonomous vessels is 40% lower than their respective conventional ships [39]. By substituting these assumptions into Equations (7) and (8), it follows that the total power ($P_{total-auto}$) and energy consumption ($E_{total-auto}$) for fully autonomous vessels are 40% lower than $P_{total-conv}$ and $\mathrm{E}_{\mathrm{total-conv}}$, respectively. Additionally, we anticipate a 30% increase in energy and power requirements to accommodate potential expansions and uncertainties in loads in the near future. Consequently, we have substituted these values into the subsequent equations in Sections 2.3–2.5 for fully autonomous vessels.

2.3. Proposed Alternative Fuels for the Marine Vessels

The use of fuel by marine engines is vital in the propulsion of ships and for providing power to other fitted systems on board. To reduce the rate of GHG emissions, the IMO has proposed enforcing stringent rules and regulations on ships' emissions. As a result, the IMO has teamed up with the Global Industry Alliance in support of low-carbon shipping in the marine industry [26,51] via the use of alternative low- and zero-carbon fuels [52]. The alternative marine fuels include conventional fuels (marine diesel oil (MDO), heavy fuel oil (HFO), marine gas oil (MGO), biofuel (B20), methane (or liquefied natural gas (LNG)), hydrogen, methanol, battery-electric, ethanol, dimethyl ether (DME), liquefied petroleum gas (LPG), ethane, and ammonia) [53,54]. The applications of the aforementioned fuels are not limited to environmental impacts but also economic criteria, fuel properties, effects on the propulsion system, and safety handling criteria [55], just to mention a few. However, for this research, only the first six alternative marine fuels will be considered due to their maturity regarding regulatory readiness levels.

2.3.1. Diesel-Propelled Marine Vessel

Formally, marine diesel fuel encompasses any type of diesel used in seagoing vessels. The three primary marine fuels are Marine Diesel Oil (MDO), Heavy Fuel Oil (HFO), and Marine Gas Oil (MGO), which are distinguished by their sulfur contents. For instance, MDO, which is readily available, is composed of various distillate blends with a minor inclusion of HFO. In addition, it possesses a slightly greater density and exhibits a lower cetane value as compared to MGO [45]. Similarly, HFO, with a higher sulfur content, requires the use of approved exhaust gas cleaning systems (or scrubbers) [56] when used onboard vessels. Likewise, MGO, comprising a blend of distillates, features a lower sulfur content compared to HFO and MDO [56–58].

Additionally, most existing marine engines and fuel-burning equipment are specifically engineered for the use of HFO, MDO, or MGO [56]. The total fuel consumption of the marine engine is determined by its overall energy usage, which is expressed as follows:

$$FC_{diesel-conv} = E_{total-conv}\, SFC_{diesel} \tag{9}$$

where $FC_{total-conv}$ denotes the fuel consumption per trip (kg), and SFC_{diesel} is the specific fuel consumption (kg/kWh). The SFC_{diesel} for slow-speed diesel vessels and high-speed diesel vessels are 0.165 kg/kWh and 0.210 kg/kWh, respectively [59,60]. Likewise, the annual mass flow rate of the total fuel consumption ($\dot{m}_{conv}$) (kg/h) is estimated as follows:

$$\begin{aligned}\dot{m}_{diesel-conv} &= \sum_{n=1}^{n=N} \frac{FC_{diesel-conv}}{(T_{crus,conv} + T_{man,conv} + T_{idle,conv})} \\ &= \sum_{n=1}^{n=N} \frac{FC_{diesel-conv}}{T_{total,conv}}\end{aligned} \tag{10}$$

where N is the total number of trips in a year (unitless), $T_{crus,conv}$ is the cruising time (hrs.), and T_{total} denotes the total hours in the context of the ships' operational profiles for the entire year (hrs.).

These fuels use the preexisting propulsions and fuel systems; therefore, the total investment costs ($IC_{\mathrm{i},conv}$) and the total operating cost of fuel ($CF_{\mathrm{total-i},conv}$) for the MDO, HFO, and MGO are determined as follows:

$$IC_{diesel-conv} = C_{in} P_{total-conv} \tag{11}$$

$$CF_{\mathrm{total-i},conv} = C_{\mathrm{i}-fuel}\, FC_{diesel-conv} \tag{12}$$

where C_i denotes the investment cost which ranges from 240 to 460 USD/kW [61], $C_{\mathrm{i}-fuel}$ is the cost of fuel (USD/kg), and i denotes the type of fuel. The cost of MDO, HFO, and MGO are 3.09 USD/kg [62], 0.511 USD/kg [63], and 0.956 USD/kg [64], respectively. In addition, the maintenance cost of the diesel-propelled conventional marine vessel is 50 USD/kW [65]. Nevertheless, the maintenance cost for the fully autonomous vessel exhibits a 15% increment, attributed to the elevated necessity of skilled ship crew members required for the maintenance of the ship while at berth [39]. This percentage increase is applied to the fully autonomous ships powered by the other alternative fuels.

2.3.2. Hydrogen-Propelled Marine Vessel

In terms of propulsion, the use of the above fuels in the preceding engines is feasible, with the exception of hydrogen, which can only be applied to four-stroke engines (shorter voyage) due to ample hydrogen storage space requirements and the need to safely handle the generated hydrogen [7]. The vessel's propulsion system is motor-driven via electrical power [1]. We proposed proton exchange membrane fuel cells (PEMFC) over the solid oxide fuel cells (SOFC) due to their quicker start-up time, strong dynamic responsiveness, operation at low temperature, and excellent power density [66].

The hydrogen fuel use in the PEMFC is produced through two different methods. The first option is via the electrolysis of water using renewable energy sources (H_2-Ren) [67]; as a result the generated hydrogen is considered to have low or net-zero emissions [53]. In addition, the second method is from fossil fuels (H_2-F). This approach generates a significant amount of CO_2 as a byproduct during its production. In contrast, the utilization of hydrogen in combustion or fuel cells does not result in CO_2 emissions [68]. Thus, the required mass of hydrogen consumption by the PEMFC ($FC_{hyd-conv}$) (kg) in both options is determined as follows [69]:

$$FC_{hyd-conv} = \frac{E_{total-conv}}{\eta_{FC}\ LHV} \tag{13}$$

where η_{FC} is the fuel cell efficiency during the beginning of life (51%), and LHV denotes the lower heating value of hydrogen (120,000 KJ/kg). In addition, the annual mass flow rate of the total hydrogen fuel consumption ($\dot{m}_{hyd-conv}$) (kg/h) is estimated by substituting $FC_{hyd-conv}$ into Equation (10). We presume that the PEMFC power system will engage in cold-ironing while at berth. This is to aid in the warming of the system until it reaches its designated operating temperature and for the production of electric power. The power demand by fuel cell components from shore power ($P_{\text{hyd,shore}-conv}$) (kW) is determined as follows:

$$P_{\text{hyd,shore}-conv} = 1.30\ \mathrm{P}_{\text{idle}-\text{conv}} \tag{14}$$

Therefore, the annual cost of cold-ironing is $P_{\text{hyd,shore}-conv}$ times the idling time and the shore power charging fees (SC_{cost}) of 0.20 USD/kWh [70]. In addition, the total investment cost ($IC_{\text{hyd}-conv}$) of PEMFC and its accessories is determined as follows:

$$IC_{\text{hyd}-conv} = C_{in-FC}\ P_{\text{hyd}-conv} + C_{acc}\ P_{\text{hyd,shore}-conv} \tag{15}$$

where C_{in-FC} is the initial investment cost for PEMFC, which is in the range of 730–2860 USD/kW [61], and C_{acc} represents the cost of accessories, which consists of a gas supply system and type IV 700 bar hydrogen storage tanks and ranges from 576 to 868 USD/kW [61]. Likewise, the replacement cost is 40% of the total component cost [71], and the annual maintenance cost is 6% of the total capital cost per lifetime [72]. The costs of green hydrogen fuel (option 1) and blue hydrogen fuel are 4.5–12 USD/kg and 1.8–4.7 USD/kg, respectively [73]. Thus, the total cost for the hydrogen fuel ($CF_{\text{hyd},conv}$) is determined as similar by substituting the cost of fuel and $FC_{hyd-conv}$ into Equation (12).

2.3.3. Battery- or Electric-Propelled Marine Vessel

The battery electric systems onboard vessels are operated in three different ways: as hybrids, plug-in hybrids, and fully electric [53]. For this research, we focus on fully electric systems, where the battery bank stores the necessary energy for propulsion and to satisfy the auxiliary loads. The advantage of electrifying ships is the elimination of GHG emissions [53]. Additionally, lithium-ion (Li-ion) batteries are considered for this research over the lead–acid batteries [74], nickel metal hybrid batteries [75], silver–zinc batteries, and open water-powered batteries due to their optimal chemical composition or battery chemistry [53,76].

To avoid excessive battery weight onboard, the battery capacity ($B_{cap-conv}$) (kWh) required by the fully battery-electric vessel is determined based on round trips using Equation (12). In addition, to prevent power failure, the battery capacity is increased by a power factor (P_f) of 20% for the conventional vessel and 40% for the fully autonomous vessel to provide onboard power supply for a round trip.

$$B_{cap-conv} = \frac{P_f\ E_{total-conv} * 2}{\eta_{Li-ion}\ \eta_{motor}\ DOD\ \eta_{inverter}} \tag{16}$$

where η_{Li-ion} is the efficiency of the lithium-ion battery (100%) [77], η_{motor} is the efficiency of the DC motor (80%) [78], DOD denotes the battery depth of discharge (80%) [78], and $\eta_{inverter}$ is the inverter efficiency (90%) [79]. Thus, Equation (8) is substituted into Equation (17), but the average speeds, average nautical distances, and average duration are used. The investment cost ($B_{invest-conv}$) and cost for the shore power connection ($BC_{cost-conv}$) for the battery bank are determined as follows:

$$B_{invest-conv} = N_{inst}\ (B_{\ cap-conv}\ B_{cost} + P_{total-conv}\ EM_{cost}) \tag{17}$$

$$BC_{cost-conv} = \quad B_{cap-conv}\ SC_{cost} \tag{18}$$

where N_{inst} is the number of times required to install the battery bank during its lifetime (unitless), B_{cost} is the initial cost of the Li-ion marine battery, which ranges from 500 to 1000 USD/kWh [61], and EM_{cost} is the cost of the electric motor which we assumed to be equal to 250 USD/kW. Also, we assumed that the battery bank needs a replacement every 4–5 years. In addition, the annual cost of shore power connection is estimated by multiplying Equation (19) by the total number of voyages in a year.

2.3.4. B20-Propelled Marine Vessel

Biodiesel is a renewable and non-toxic fuel that offers a cleaner combustion option, serving as a noteworthy alternative to conventional diesel. Its combustion results in diminished air emissions, encompassing reductions in soot, smoke, carbon monoxide, and GHG emissions [80], rendering it highly environmentally friendly.

In this research, we explore a biodiesel–diesel blend, denoted as B20. This composite fuel consists of 20% biodiesel and 80% conventional diesel [81]. The adoption of B20 in lieu of traditional diesel enables ships to achieve a potential reduction of up to 20% in GHG emissions [80].

The total B20 fuel consumption ($FC_{B20-conv}$) by the conventional vessel is determined as follows:

$$FC_{B20-conv} = E_{total-conv}\ (0.20\ \ SFC_{biodiesel} + 0.80\ SFC_{diesel}) \tag{19}$$

where specific fuel consumption for biodiesel ($SFC_{biodiesel}$) is 0.74 kg/kWh [82,83]. Similarly, the mass flow rate of the total fuel consumption for B20 ($\dot{m}_{B20-conv}$) is estimated by dividing the annual $FC_{B20-conv}$ by $T_{total,conv}$.

The total investment cost of replacing the existing diesel power system with B20 power system is calculated by multiplying the initial investment cost of the B20 system, which ranges from 240 to 460 USD/kW [61], by the total power ($P_{total-conv}$). Similarly, the total cost of operating the B20 fuel is estimated by multiplying the cost of B20 fuel, which is 3.980 USD/kg [84], by the total fuel consumption ($FC_{diesel-conv}$). The maintenance cost for a ship powered by B20 is comparable to that of a vessel powered by diesel.

2.3.5. Liquefied Natural Gas (LNG)-Propelled Marine Vessel

Liquefied natural gas (LNG) is regarded as a feasible substitute fuel for diverse classes of ships, encompassing those involved in deep-sea, short-sea, and inland navigation. The evaluation of various technologies has raised significant apprehensions regarding the potential shift of ships to LNG as the primary fuel source in recent times [85]. Furthermore, the current bunkering strategies implemented by shipping companies have a pivotal influence on the decision-making process between LNG and low-sulfur fuel [86].

The fuel consumption of the LNG marine engine encompasses not just the direct utilization of LNG but also incorporates the consumption of pilot fuel [85]. The purpose of the pilot fuel is to initiate the combustion process and to ensure a dependable source of ignition [87]. This dual-fuel approach enables the vessel to curb the emission of pollutants. The mixing proportion of LNG and pilot fuel in a dual-fuel system is 98% and 2%, respectively [88].

The total fuel consumption by LNG-propelled ship is calculated as follows:

$$FC_{LNG-conv} = E_{total-conv}\ \left(0.98\ SFC_{LNG} + 0.02\ SFC_{pilot\ fuel}\right) \tag{20}$$

where the SFC_{LNG} and $SFC_{pilotfuel}$ represent the specific fuel consumption for LNG (0.15 kg/kWh) and pilot fuel (0.02 kg/kWh) [85], respectively.

The overall investment cost for replacing the existing diesel power system with an LNG power system is determined by multiplying the initial investment cost of 400USD/kW [61] by $P_{total-conv}$. Likewise, the total operating cost of LNG fuel is estimated by multiplying the cost of LNG fuel, which is 1.560 USD/kg [63], by the total fuel consumption ($FC_{LNG-conv}$). The maintenance cost for the LNG-propelled ship is 0.005 USD/kWh [89].

2.3.6. Methanol-Propelled Marine Vessel

Currently, methanol (MeOH) stands out as a prospective alternative to traditional fuels in maritime transport. Notably, methanol exhibits a heat of vaporization nearly four times higher than that of diesel fuel. This characteristic implies that methanol requires more heat energy for vaporization, leading to a charge cooling effect and a subsequent reduction in cylinder temperature. Furthermore, the charge cooling effect contributes to a reduction in NO_X emissions, attributable to its lower combustion temperature compared to diesel fuel [90,91].

In this study, a combustion strategy involving the use of methanol–diesel is employed for ships powered by methanol. The primary fuel comprises 98% methanol, supplemented by 2% pilot fuel added to the methanol–air mixture within the cylinder to initiate ignition [54].

The calculation of fuel consumption for the ship powered by methanol ($FC_{meth-conv}$) is as follows:

$$FC_{meth-conv} = E_{total-conv}\ \left(0.98\ SFC_{meth} + 0.02\ SFC_{pilot\ fuel}\right) \tag{21}$$

where SFC_{meth} is the specific fuel consumption of methanol which is equal to 0.48964 kg/kWh [92].

The total investment cost for replacing the current diesel power system with a new methanol power system is computed by multiplying the initial investment cost of 265–505 USD/kW [61] by the total converted power ($P_{total-conv}$). Similarly, the total operational cost of methanol is estimated by multiplying the cost, set at 0.520 USD/kg [63], by the total fuel consumption ($FC_{meth-conv}$). The maintenance cost for the ship propelled by methanol is equivalent to that of the ship powered by diesel.

2.4. Environmental Impact and Environmental Cost Assessments

The marine vessels used for this case study are an HSPF and a tugboat, which are known to cause a very high rate of emissions due to their speed and variable modes of transportation [32]. Additionally, the internal combustion of marine fuels emits numerous pollutants into the atmosphere. Therefore, this section presents a detailed discussion on the mass emission rate, global warming potential, environmental impact, and damage cost.

2.4.1. Mass Emission Rate

The mass emission rate is defined as the discharge rate of a pollutant, denoted by its weight per unit of time [93]. Similarly, the emissions factor refers to the quantity of pollutants emitted into the atmosphere relative to a specific activity [94–96]. The main pollutants associated with marine alternative fuels include carbon monoxide (CO), CO_2, sulfur oxides (SO_X), nitrogen oxide (NO_X), nitrous oxide (N_2O), particulate matter (PM) or black carbon, and unburned hydrocarbons (UHC) or methane (CH_4) [97,98]. The mass emission rate by each pollutant for the alternative fuels is expressed as follows:

$$\dot{m}_{ij,conv} = \dot{m}_{conv}\; EF_j \tag{22}$$

where $\dot{m}_{ij,conv}$ is the mass emission rate of each pollutant (kg/h), i is the type of alternative marine fuel, j denotes the type of pollutant from marine fuel (unitless), and EF_j denotes the emission factor (g/kg-fuel), which is tabulated in Table 5.

Table 5. Emission factors (EF) for marine alternative fuels (g/kg fuel).

Alternative Fuels	CO_2	CO	N_2O	NOx	SOx	PM	CH_4
B20 (Biofuel)	- [99]	2.52 [81]	0.15 [99]	61.21 [99]	2.64 [99]	1.02 [99]	0.06 [99]
HFO	3114 [98]	2.87 [98]	0.18 [98]	78.61 [98]	50.83 [98]	7.53 [98]	0.05 [98]
Hydrogen	- [99]	- [99]	- [100]	- [99]	- [99]	- [99]	- [100]
LNG	2753 [98]	3.57 [98]	0.10 [98]	10.95 [98]	0.03 [98]	0.18 [98]	51.6 [99]
Methanol	1375 [99]	- [98]	- [99]	8 [99]	- [98]	- [99]	- [99]
MGO	3206 [101]	0.70 [101]	0.18 [1] [98]	51.23 [101]	2.74 [1] [98]	0.97 [1] [98]	0.05 [1] [98]
MDO	3206 [98]	2.54 [98]	0.18 [98]	57.62 [98]	2.74 [98]	0.97 [98]	0.05 [98]

[1] The designation “MDO” in the 4th IMO GHG study refers to the emission factors (EFs) for both MGO and MDO. Consequently, some of the EFs assigned to MDO are also attributed to MGO.

The table mentioned above presents the emission factors (EFs) for all alternative fuels under investigation, excluding electricity. Additionally, the EFs for B20 are sourced from references [81,99], while hydrogen is considered to have zero emissions according to references [99,100]. The EFs for HFO and MDO are derived exclusively from the Fourth IMO GHG report [98], whereas the EFs for LNG and methanol are obtained from both [98,99]. Furthermore, the values for MGO are sourced from [98,101]. In addition, the Total Mass Emission Rate (TMER) of the pollutants from a particular alternative fuel is calculated by aggregating the individual mass emission rates of the pollutants emitted by that specific alternative fuel.

2.4.2. Global Warming Potential (GWP)

The global warming potential is a measure of the amount of energy a single ton of gas will consume over a specific period compared to one ton of CO_2. The greater the GWP, the more a particular gas contributes to heating the earth in comparison to CO_2 over that period [102]. Additionally, the typical time horizon used for regulating the GWP assessments is 100 years [103,104]. Although NOx and SOx are not classified as greenhouse gasses (GHGs), they can exert indirect effects on the climate. Their primary impacts are localized, influencing air quality and human health; however, they may also have broader environmental repercussions. Consequently, they were included in the GWP calculations; thus, the total GWP of emissions ($GWP_{ij,conv}$) indicated by the GWP index ($\frac{kg}{h}$ CO_2 eqv.) is expressed as follows [105]:

$$TGWP_{ij,conv} = \sum_{n=1}^{n=i} \dot{m}_{ij,conv}\, GWP_j \tag{23}$$

where GWP_{j} denotes the GWP value for each pollutant (unitless), as shown in Table 6.

Table 6. Global warming potentials values for greenhouse gasses, environmental impact factor, and environmental costs of emissions.

Pollutants	Global Warning Potential (GWP) Value (Unitless)	Environmental Impact Factor, b (mPts/kg)	Environmental Cost of Emission, C (USD/kg) [2]
CO_2	1 [102–106]	5.45 [105,107,108]	0.128 [105,107]
CO	1 [105]	8.36 [105,107,108]	0.201 [105,107]
N_2O	273 [102]	163.8 [1] [109]	2.66 [108]
NOx	310 [105]	2749.36 [105,110]	5.912 [105]
SOx	23,900 [105]	1499.37 [105]	9.670 [105]
PM	460 [111]	240.00 [112]	40.40 [113]
CH_4	28 [106–114]	114.62 [105]	2.78 [105,107]

[1]. Converted from KG/TJ to mPts/kg. [2]. These values have been converted to USD.

The values for global warming potential (GWP), environmental impact factor (b), and environmental cost of each emission (C) are presented in Table 6. However, the cost values (C) are originally reported in GBP/kg, and we have converted them to USD/kg to ensure consistency with the context of our research conducted in North America.

2.4.3. Environmental Impact and Damage Cost

The environmental impact (EI) is defined as the change to the environment resulting from a direct activity, which can have either adverse or beneficial consequences for the inhabitants of an ecosystem [115]. The total EI (TEI) for the marine engine emissions can be expressed as follows:

$$TEI_{ij,conv} = \sum_{n=1}^{n=i} \dot{m}_{ij,conv}\, b_j \tag{24}$$

where $TEI_{ij,conv}$ signifies the total environmental impact (mPts/h) and b_{j} denotes the environmental impact factor (mPts/kg) in Table 6.

In addition, the environmental damage cost (EDC) is defined as the cost of emissions released into the atmosphere by the combustion of the marine alternative fuels [116]. Thus, the total EDC can be determined as follows:

$$TEDC_{ij,conv} = \sum_{n=1}^{n=1} \dot{m}_{ij,conv}\, C_j \tag{25}$$

where $TEDC_{ij,conv}$ denotes the total environmental damage cost (USD/h) and C_j denotes the environmental cost of emission (USD/kg) in Table 6.

2.5. Total Cost Assessment

The total cost assessment is the process of incorporating environmental cost into the cost analysis for a long period of time [117]. The cost analysis comprises the capital cost, operating cost, voyage cost, and net present value, which are discussed in detail in the subsections.

2.5.1. Capital Cost

Capital cost refers to the expense associated with the ship. Additionally, the capital cost for the conventional ferry varies based on the marine vessel's specific particular and conditions. The elimination of onboard ship crew, hoteling systems, and certain deckhouses for the fully autonomous ship directly affects the capital cost. Nevertheless, the implementation of the advanced sensors and control systems for onboard navigation and lookout systems at the shore control center (SCC) leads to an increase in capital costs due to a redundancy in these systems, resulting in an overall increase of 10% [65].

2.5.2. Voyage Cost

The voyage cost consists of the fuel cost for the engines, the environmental damage cost, and the port call costs. However, the port call cost is assumed to be 20% higher for the fully autonomous marine vessels due to the implementation of a new framework and assistance from the SCC crew. Therefore, the annual voyage cost ($VC_{annual,conv}$) for the ship's lifetime is determined as follows:

$$VC_{\text{annual},conv} = \left(\text{TEDC}_{\text{ij,conv}}\ T_{total,conv} + D_{total-days,conv}\ PC_{\text{total}-\text{i},conv} + CF_{\text{total}-\text{i},conv}\right) \quad (26)$$

where $T_{total,conv}$ is the total hours of operation per year (hrs.), $D_{total-days,conv}$ is the total days of voyage in a year (days), $PC_{\text{total}-\text{i},conv}$ is the port cost (124 USD/day) [118], and $FC_{\text{total}-\text{i},conv}$ is the annual fuel cost.

2.5.3. Net Present Value (NPV)

The net present value is the difference between the present cash inflows and outflows over a given period, at a discounted rate of today's value. The cashflow comprises the investment cost, operating cost, voyage cost, and cost of revenue. Although the vessels chosen for this research have been in operation for more than a decade, we assume their respective engines will be replaced after 25 years, as well-maintained marine engines can last for approximately 40 years [119]. Thus, the NPV for conventional vessels with a lifetime (t) of 25 years at a discount rate (r) of 5.50% [120] is determined as follows:

$$NPV_{conv} = \left(\sum_{t=1}^{25}\left(\frac{[cashflow]_t}{[1+r]^t}\right)\right) - IC_{\text{i},conv} \quad (27)$$

where $IC_{\text{i},conv}$ represents the investment cost of the conventional vessel for the different marine fuels as specified in Sections 2.3.1–2.3.3. However, the investment cost for the fully autonomous ships ($IC_{\text{i},auto}$) is expected to be 30% higher than $IC_{\text{i},conv}$ due to the newly fitted advanced sensors and control systems [65].

3. Results

This study investigates KPIs for marine alternative fuels across both conventional and autonomous vessels, including total mass emission rate (TMER), total global warming potential (TGWP), total environmental impact (TEI), total environmental damage cost (TEDC), and net present value (NPV), as illustrated in Figure 3. The findings reveal that alternative fuels, such as H2-Ren, H2-F, and Elec, exhibit zero environmental emissions and costs during ship operations. In contrast, traditional fuels like HFO, MDO, MGO, and MeOH demonstrate the highest TMER due to their pollutant constituents and mass flow rates, with B20 and LNG showing comparatively lower emissions. To illustrate, the TMER associated with traditional fuels is significantly impacted by their constituent pollutants and mass flow rates, whereas B20 and LNG exhibit a contrasting trend across different vessel types. Additionally, HFO ranks highest in TGWP, indicating substantial contributions to global warming, while LNG and MeOH have the lowest potential, suggesting a more favorable environmental profile. Regarding TEI, B20 has the highest TEI value, primarily due to incomplete combustion and increased NOx emissions, whereas LNG shows the lowest TEI value, indicating a lesser overall environmental impact. In terms of TEDC, HFO exhibits the highest TEDC, attributable to the environmental damage caused by SOx emissions, while LNG presents the lowest TEDC, showcasing its advantages in terms of environmental costs. All proposed marine fuels demonstrate viable economic values (NPVs), with LNG achieving the highest NPV owing to its fuel efficiency, lower capital costs, and significant environmental benefits, including reduced emissions of SOx, PM, NOx, and TGWP.

Moreover, the analysis indicates that alternative marine fuels for autonomous vessels yield better environmental and economic outcomes compared to conventional vessels. This improvement is primarily due to reductions in fuel consumption, energy usage, operating costs, and the overall environmental footprint. A comparative analysis based on vessel types reveals that alternative marine fuels for high-speed passenger ferries (HSPF) achieve lower emissions, benefiting from high operational speeds and engine efficiency. In contrast, tugboats emit more pollutants despite shorter navigation routes due to their lower operating speeds, continuous operation, and port activities. However, alternative fuels for tugboats exhibit higher NPV values than those for HSPF, a trend attributed to greater utilization rates, stable revenue streams, lower operating costs per unit of time or distance traveled, and reduced initial capital investments.

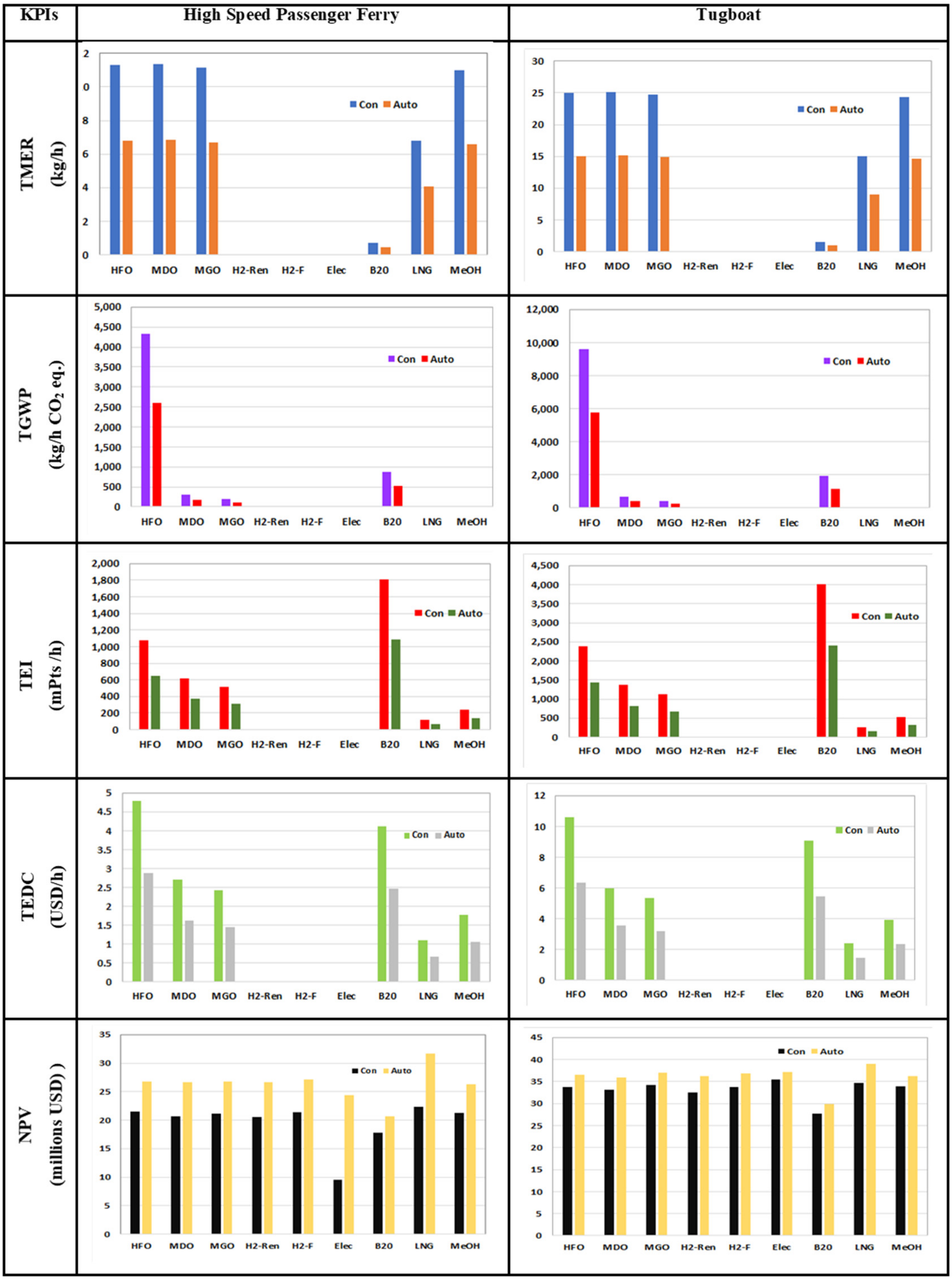


Figure 3. Results of the KPIs for the conventional and fully autonomous ships: HSPFs and tugboats.

In summary, the data presented in Figure 3 underscore the significant differences in environmental impact and economic viability among various marine fuels. By illustrating these KPIs, this figure serves to enhance the understanding of the advantages and challenges associated with alternative fuels in the marine sector, particularly in relation to both conventional and autonomous vessels.

3.1. Sensitivity Analysis

In this study, a sensitivity analysis is conducted to examine the critical technical and economic input variables with respect to the NPV of alternative marine fuels for both conventional and fully autonomous vessels. The input parameters considered for the analysis include rate, fuel costs, emission costs, vessel speed, load factor, and nautical miles (or navigation distance). These input parameters are systematically adjusted within a range from −50% to +50%, with increments of 10%. The outcomes of the sensitivity analyses for each vessel are depicted in Figures 4–7. Specifically, Figure 4 illustrates the sensitivity analysis for the conventional high-speed passenger ferry (HSPF), while Figure 5 focuses on the sensitivity analysis for the fully autonomous HSPF. Figure 6 depicts the sensitivity analysis for the tugboat, and finally, Figure 7 presents the sensitivity analysis for the fully autonomous tugboat. It can be inferred that the figures from the sensitivity analyses demonstrate a consistent trend.

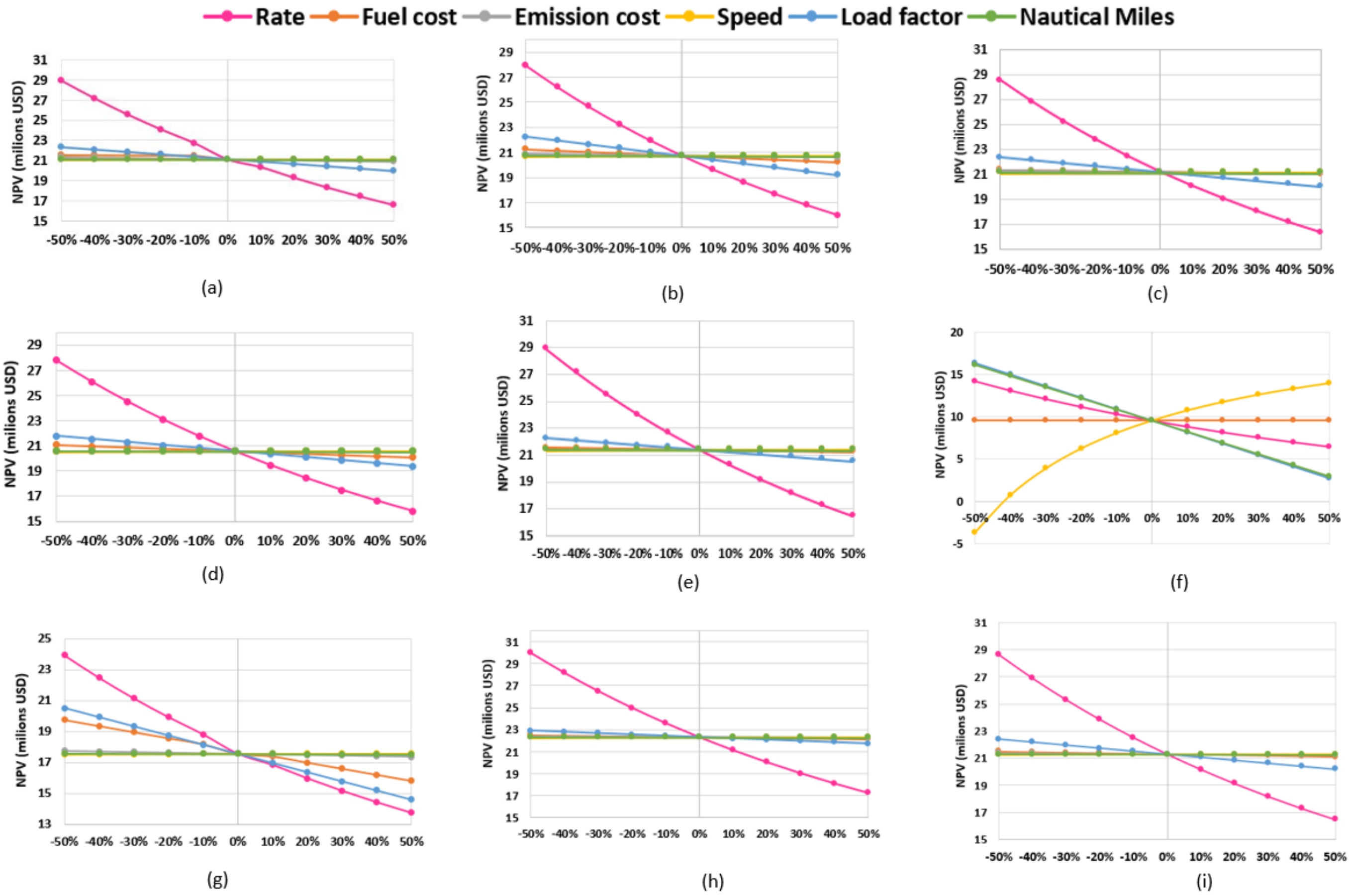


Figure 4. Sensitivity analysis for conventional HSPF: (**a**) HFO, (**b**) MDO, (**c**) MGO, (**d**) H2 Ren, (**e**) H2-F, (**f**) Elec, (**g**) B20, (**h**) LNG, and (**i**) MeOH.

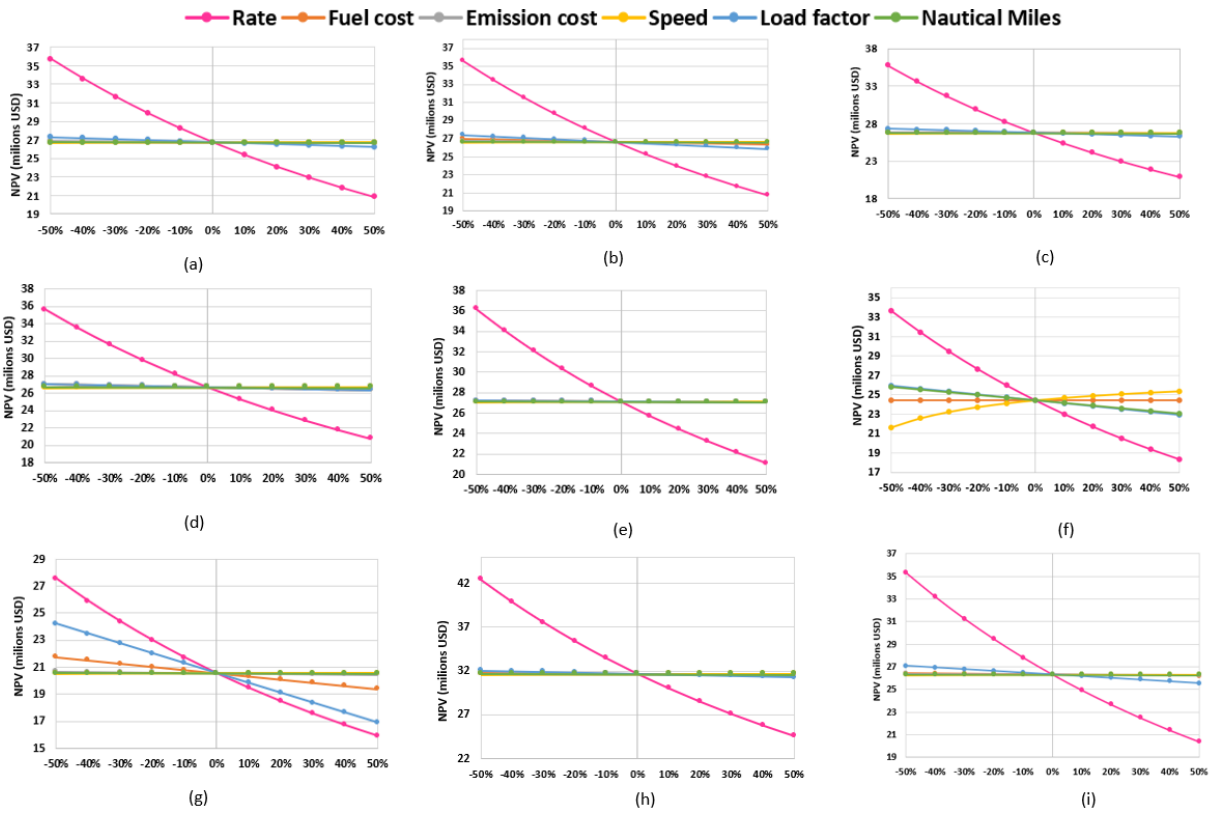


Figure 5. Sensitivity analysis for fully autonomous HSPF: (**a**) HFO, (**b**) MDO, (**c**) MGO, (**d**) H_2 Ren, (**e**) H_2-F, (**f**) Elec, (**g**) B20, (**h**) LNG, and (**i**) MeOH.

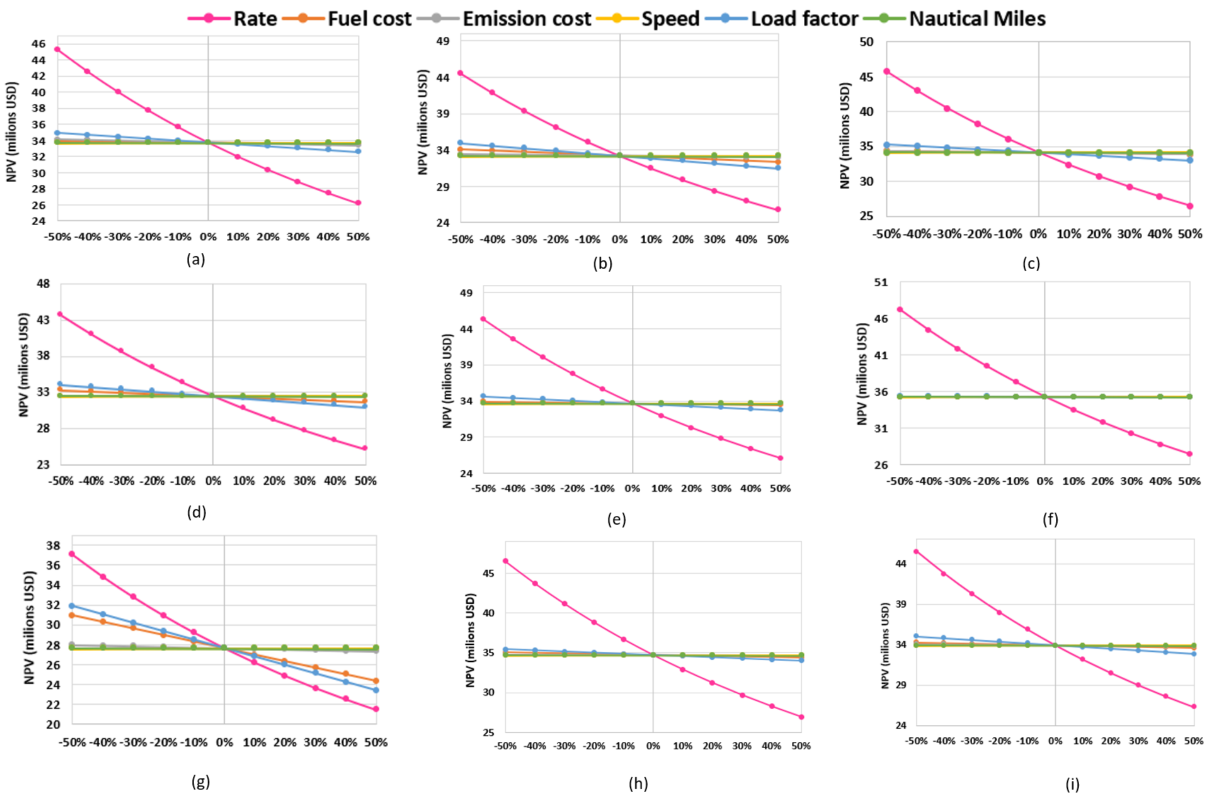


Figure 6. Sensitivity analysis for conventional tugboat: (**a**) HFO, (**b**) MDO, (**c**) MGO, (**d**) H_2 Ren, (**e**) H_2-F, (**f**) Elec, (**g**) B20, (**h**) LNG, and (**i**) MeOH.

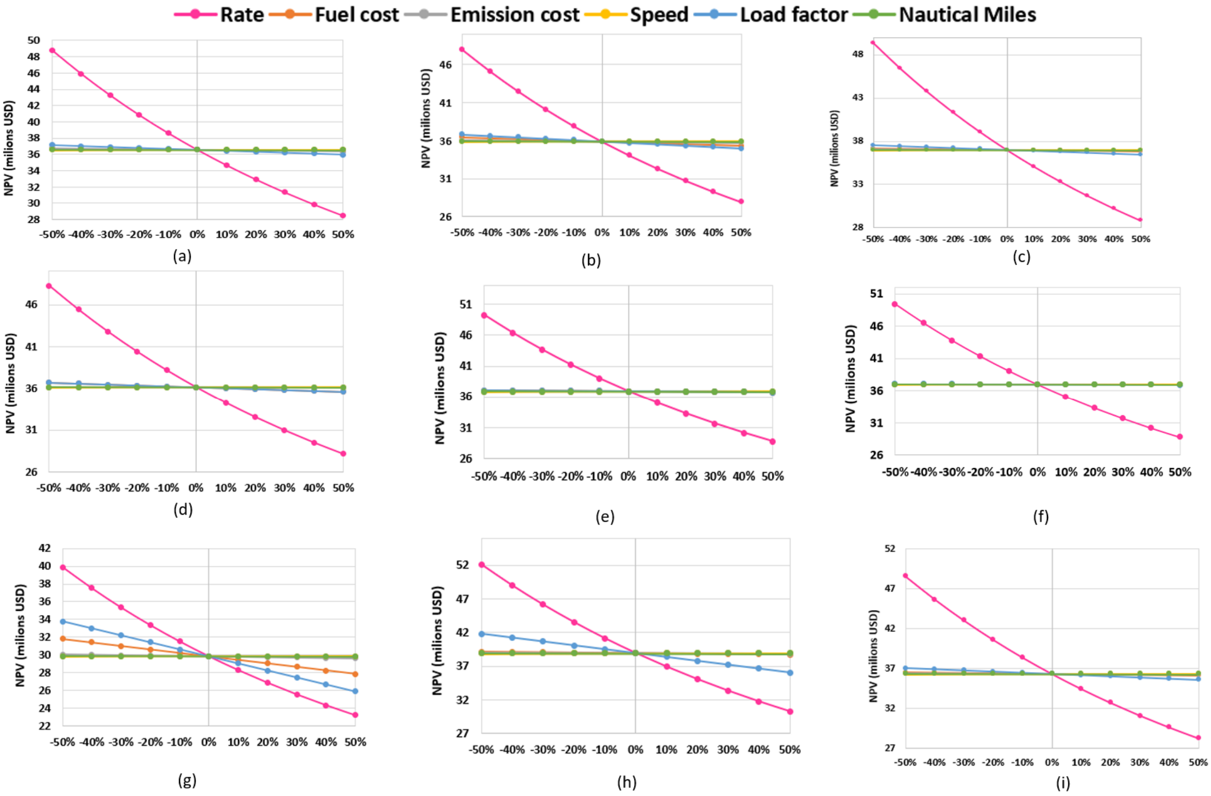


Figure 7. Sensitivity analysis for fully autonomous tugboat: (**a**) HFO, (**b**) MDO, (**c**) MGO, (**d**) H_2 Ren, (**e**) H_2-F, (**f**) Elec, (**g**) B20, (**h**) LNG, and (**i**) MeOH.

The findings reveal that interest rate variation has the most significant impact on NPV values compared to the other five input parameters. Lowering the rate increases NPV by raising the present value of future cash flows, whereas increasing the rate decreases NPV. LNG consistently achieves the highest NPV across all vessel types, while Elec and B20 exhibit the lowest NPV for conventional and fully autonomous HSPFs, respectively. Similarly, B20 has the lowest NPV for both conventional and fully autonomous tugboats.

Following interest rates, load factor variation emerges as the second most critical parameter. A lower load factor results in higher NPV due to reduced operational and environmental costs per unit of distance traveled, while a higher load factor decreases NPV. Again, LNG records the highest NPV for all vessels, while Elec and B20 have the lowest NPV for conventional and fully autonomous HSPFs, respectively, also showing the lowest NPV for both conventional and fully autonomous tugboats.

Fuel cost variation is the third most significant input parameter with lower NPV values. Lower fuel costs lead to higher NPV due to reduced operational expenses per unit of distance traveled, while higher fuel costs have the opposite effect. LNG maintains the highest NPV for all ships, while Elec and B20 present the lowest NPV for conventional and fully autonomous HSPFs, respectively. Similarly, B20 records the lowest NPV for both conventional and fully autonomous tugboats.

Emission cost variation is the fourth most significant input parameter with low NPV values. Lower emission costs increase profitability due to reduced operational and environmental expenses, while higher emission costs have the opposite effect. LNG attains the highest NPV for all ships, while B20 records the lowest NPV.

Nautical miles variation is ranked fifth, with shorter distances leading to reduced fuel consumption, emissions, and associated costs, resulting in higher NPV values. However, longer distances have the opposite effect. LNG records the highest NPV for all ships. Elec and B20 have the lowest NPV for conventional and fully autonomous HSPFs, respectively. B20 also records the lowest NPV for both conventional and fully autonomous tugboats.

Lastly, speed variation is identified as the least significant parameter, recording the lowest NPV values among all parameters. Reducing ship speed leads to extended operational times, increased emissions, and higher fuel and emission costs per unit of distance traveled, which impacts profitability and reduces NPV. Conversely, increasing ship speed results in the opposite outcome. LNG achieves the highest NPV for all ships. Elec has the lowest NPV for both conventional and fully autonomous HSPFs. Similarly, B20 records the lowest NPV for both conventional and fully autonomous tugboats.

In summary, LNG is determined to be the optimal choice for the four proposed vessels in this study. Autonomous vessels consistently achieved the best results in all scenarios, supporting the argument that implementing fully autonomous vessels would not only reduce pollutant emissions but also increase both profitability and potential revenue. Consequently, the subsequent section focuses exclusively on LNG-fueled vessels for the proposed fully autonomous HSPF and tugboat, using the same input parameters simultaneously to examine their respective impacts on NPV.

3.2. Stochastic Analysis

This study employs stochastic analysis to ascertain the NPV of LNG-powered fully autonomous vessels, utilizing probability and random sampling techniques to assess performance and economic outcomes amidst uncertainty. Each input parameter is varied between a lower bound of −50% and an upper bound of +50% of its base value, with these variations applied simultaneously and uniformly across 1000 model runs.

Figure 8 presents the results of the tornado analysis and cumulative distribution function (CDF) for both the fully autonomous HSPF and tugboat. In the tornado analysis, which ranks uncertain input parameters by their impact, the rate emerges as the most critical factor affecting NPV estimates, suggesting that improving economic rate accuracy and reducing uncertainty could enhance these estimates. The load factor follows as the next crucial parameter, highlighting the significance of efficient load factor management in controlling operational costs. Therefore, enhancing energy efficiency through optimized hull designs and advanced propulsion systems is crucial for enhancing economic performance. The emission cost ranks third, indicating significant costs associated with regulatory compliance, which can fluctuate based on changes in regulations and fuel quality, underscoring the necessity for emission reduction technologies. For the fully autonomous HSPF, speed and nautical distance are significant factors, while fuel cost has the least impact on NPV variability. In contrast, for the fully autonomous tugboat, fuel cost is significant, followed by speed and nautical distance. These findings stress the importance of strategic rate setting, energy-efficient technologies, compliance with IMO regulations, and optimized operational planning for financial success.

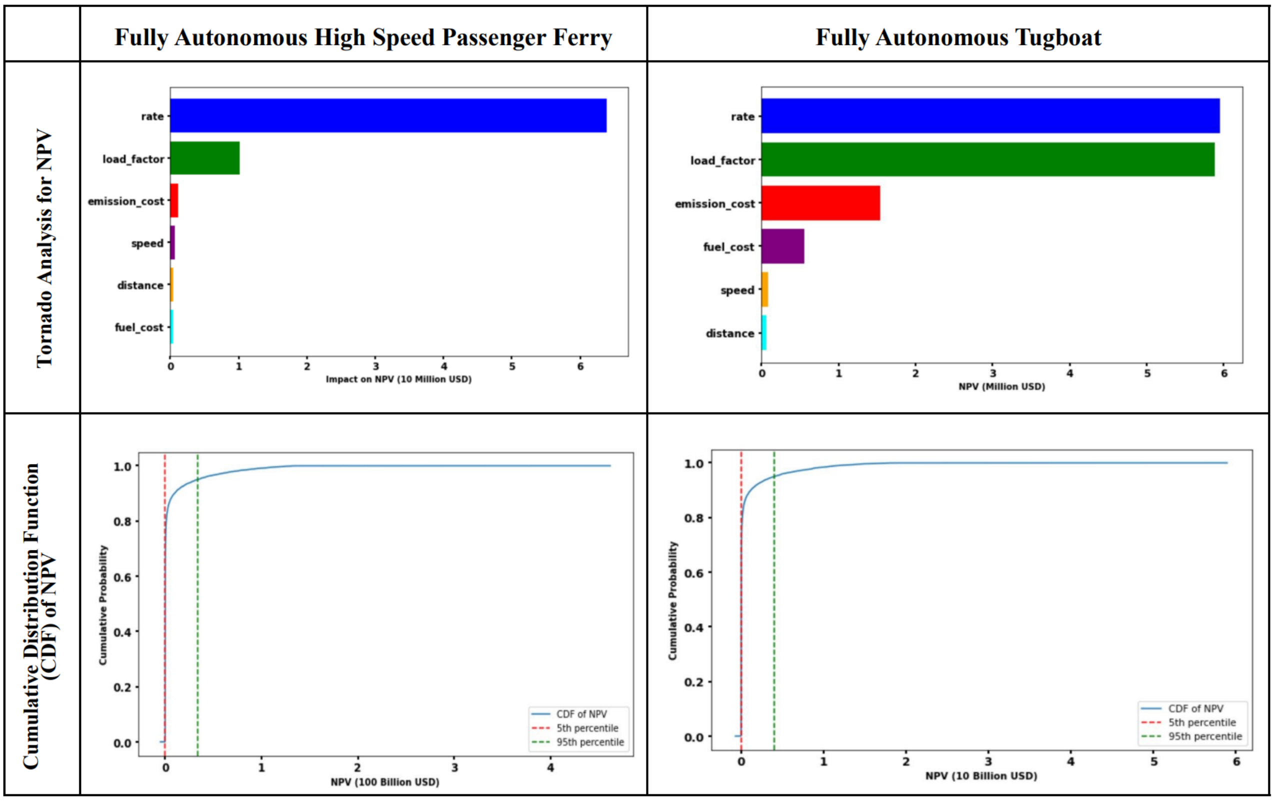


Figure 8. Result of stochastic analysis for fully autonomous HSPF and tugboat powered by LNG fuel.

The stochastic analysis illustrates the range of potential financial outcomes for LNG-powered fully autonomous vessels through the CDF of the NPV. At the 5th percentile, NPV values for both vessels are zero, suggesting the possibility of no financial gain or a potential loss in worst-case scenarios, emphasizing the need for effective risk management. At the 95th percentile, NPV for the fully autonomous HSPF and tugboat is approximately USD 35 billion and USD 4 billion, respectively, indicating substantial profitability under favorable conditions. This extensive range illustrates the considerable uncertainty and variation associated with critical input parameters. These observations emphasize the necessity for the meticulous management and optimization of these factors to enhance economic feasibility and address risks. The outcomes provide valuable perspectives for guiding strategic decisions, validating investments, and ensuring compliance with regulatory and environmental objectives in the marine sector.

In brief, this stochastic analysis reveals critical insights into the net present value (NPV) of LNG-powered fully autonomous vessels, identifying interest rate, load factor, and emission costs as key determinants. The analysis underscores the potential for zero NPVs in adverse scenarios, highlighting the importance of effective risk management. Conversely, favorable conditions could yield substantial profitability, with NPVs reaching approximately USD 35 billion for high-speed passenger ferries and USD 4 billion for tugboats. These findings emphasize the need for strategic decision-making and operational optimization to ensure economic viability in the marine sector.

4. Discussion

The pursuit of improved energy efficiency and reduced emissions in maritime operations is increasingly vital as the industry grapples with sustainability challenges. This study enhances the understanding of alternative marine fuels by conducting a comprehensive analysis using key performance indicators (KPIs), such as total mass emission rate (TMER) and net present value (NPV). This discussion contextualizes our findings within the existing literature, highlighting the contributions and unique insights of our research.

The findings align with previous studies, such as those by Chen and Yang [31], which utilized automatic identification system (AIS) data for emission estimations. Our approach extends this methodology by integrating AIS data to evaluate both environmental and economic impacts across conventional and autonomous vessels, offering a more nuanced understanding of real-time operational dynamics. This integration addresses a noted gap in prior research that often relied on vessel-specific data, potentially limiting the applicability of findings.

Furthermore, our results corroborate the work of Aarskog et al. [32], which highlighted the economic feasibility of fuel cell (FC) propulsion. Our study builds on this by showcasing the zero emissions of hydrogen and electric options, contrasting starkly with traditional fuels like HFO and MDO, which exhibited the highest TMER. This reinforces the necessity for adopting cleaner fuels and aligns with calls for transitioning towards sustainable maritime practices.

The analysis conducted by Jafarzadeh and Schjølberg [33] regarding optimal propulsion power utilization supports our findings on the operational efficiency of alternative fuels. Our results indicate that high-speed passenger ferries benefit significantly from alternative fuels, achieving lower emissions due to enhanced engine efficiency at operational speeds. This observation diverges from previous studies that identified limited benefits in hybrid or electric integration for certain vessel types, such as ocean-going reefers, suggesting that our findings may indicate a broader applicability of alternative fuels for high-speed vessels.

Moreover, our research contributes a comprehensive mathematical model for assessing environmental and economic impacts, a feature underexplored in the existing literature. This model, designed specifically for selected ships, offers stakeholders a practical tool for evaluating fuel options in line with environmental policies. Our stochastic analysis further distinguishes our study, allowing for sensitivity assessments that have not been extensively covered in prior research. This analysis reveals how variations in load factors and operating conditions significantly affect NPVs, an aspect that previous studies often overlooked.

While many studies, including those by Kouzelis et al. [34] and Kosmas and Acciaro [35], have focused on specific alternative fuels, our holistic approach enables a direct comparison of multiple fuels across various vessel types and operational profiles. This comparative analysis not only highlights the economic viability of LNG and biofuels but also underscores the necessity for adaptive regulatory measures to promote sustainable fuel use.

In conclusion, this study provides valuable insights into the environmental and economic assessments of alternative marine fuels, building on previous research while introducing innovative methodologies. By addressing the simultaneous analysis of economic feasibility and emissions for both conventional and autonomous vessels, our findings advance the discourse on sustainable shipping solutions. The comprehensive mathematical model and stochastic analysis presented here serve as critical tools for industry stakeholders, guiding decisions that align with both ecological sustainability and economic performance. As the maritime sector evolves, the adoption of alternative fuels will be essential in achieving the dual goals of reducing emissions and enhancing energy efficiency, ultimately contributing to the global commitment to sustainable development.

5. Conclusions

This research paper presents an effective approach aimed at reducing marine pollution and costs by determining the optimal marine alternative fuel for short-sea operating shipping vessels while maximizing energy efficiency. Utilizing mathematical models in a Python environment, analyses are conducted on both conventional and fully autonomous HSPFs and tugboats, employing bottom-up approaches, analyzing ship operating phases, and utilizing the global warming potential approach.

The study's objective is to identify the optimal marine fuel with the highest NPV and minimal emissions that aligns with IMO regulatory standards, environmental objectives, and economic uncertainties. The analysis integrates ships' AIS data, specifications, and port information to determine power, energy, and fuel consumption while incorporating parameters of proposed marine alternative fuels for environmental and cost analyses. In addition, the key performance indicators (KPIs) are investigated for marine alternative fuels across both conventional and autonomous vessels, including TMER, TGWP, TEI, TEDC, and NPV. Sensitivity analyses are conducted for each alternative fuel to validate results, and a stochastic analysis is performed on the optimal marine fuel.

The study identifies LNG fuel as the optimal choice for the proposed vessels, with autonomous vessels consistently yielding favorable results. Sensitivity analyses reveal the critical technical and economic input variables that affect NPV for both conventional and autonomous vessels. Additionally, the stochastic analysis demonstrates the range of potential financial outcomes for LNG-powered fully autonomous vessels.

Despite significant constraints due to data limitations, the study underscores the importance of conducting further research to assess the techno-economic impacts and emissions effects of fully autonomous vessels across different navigation routes. Overall, the findings emphasize the need for the meticulous management and optimization of critical input parameters to enhance economic feasibility and address risks, providing valuable insights for decision-making, justifying investments, and ensuring regulatory compliance in the marine sector.

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