Journal of
Marine Science and Engineering

MDPI

Article

Comparative Analysis of the Alternative Energy: Case of Reducing GHG Emissions of Estonian Pilot Fleet

Riina Otsason [1], Andres Laasma [1], Yiğit Gülmez [2], Jonne Kotta [1,3,*] and Ulla Tapaninen [1]

[1] Estonian Maritime Academy, Tallinn University of Technology, Kopli 101, 11712 Tallinn, Estonia; riina.otsason@taltech.ee (R.O.); andres.laasma@taltech.ee (A.L.); ulla.tapaninen@taltech.ee (U.T.)
[2] Teknologian Tutkimuskeskus VTT Oy, Kivimiehentie 3, 02150 Espoo, Finland; yigit.gulmez@vtt.fi
[3] Estonian Marine Institute, University of Tartu, Mäealuse 14, 12618 Tallinn, Estonia
* Correspondence: jonne.kotta@taltech.ee

Abstract: The FuelEU Maritime Regulation, part of the European Union's (EU's) Fit for 55 initiative, aims to achieve significant reductions in greenhouse gas (GHG) emissions within the maritime sector. This study assesses the feasibility of alternative fuels for the Estonian pilot fleet using a Well-to-Wake (WtW) life cycle assessment (LCA) methodology. Operational data from 18 vessels, sourced from the Estonian State Fleet's records, were analyzed, including technical specifications, fuel consumption patterns, and operational scenarios. The study focused on marine diesel oil (MDO), biomethane, hydrogen, biodiesel, ammonia, and hydrotreated vegetable oil (HVO), each presenting distinct trade-offs. Biomethane achieved a 59% GHG emissions reduction but required a volumetric storage capacity up to 353% higher compared to MDO. Biodiesel reduced GHG emissions by 41.2%, offering moderate compatibility with existing systems while requiring up to 23% larger storage volumes. HVO demonstrated a 43.6% emissions reduction with seamless integration into existing marine engines. Ammonia showed strong potential for long-term decarbonization, but its adoption is hindered by low energy density and complex storage requirements. This research underscores the importance of a holistic evaluation of alternative fuels, taking into account technical, economic, and environmental factors specific to regional and operational contexts. The findings offer a quantitative basis for policymakers and maritime stakeholders to develop effective decarbonization strategies for the Baltic Sea region.

Keywords: shipping; pilotage; GHG emissions; alternative fuels

check for updates

Received: 3 January 2025
Revised: 25 January 2025
Accepted: 4 February 2025
Published: 6 February 2025

Citation: Otsason, R.; Laasma, A.; Gülmez, Y.; Kotta, J.; Tapaninen, U. Comparative Analysis of the Alternative Energy: Case of Reducing GHG Emissions of Estonian Pilot Fleet. *J. Mar. Sci. Eng.* **2025**, *13*, 305. https://doi.org/10.3390/jmse13020305

1. Introduction

The European Commission has adopted the Fit for 55 initiative to align the EU's climate, energy, transport, and taxation policies with its target of reducing net GHG emissions by at least 55% by 2030 [1]. By 2050, the European Green Deal aims for net-zero greenhouse gas emissions. Maritime transport, which accounts for 77% of European external trade and 35% of all trade, plays a critical role in the international supply chain and economy [2]. However, it contributes significantly to the EU's total GHG emissions, representing 13.5% of all emissions from the transport sector, following road transport (71%) and aviation (14.4%).

The current International Maritime Organization (IMO) and EU GHG emission measures focus on ships larger than 5000 gross tons (GT); some measures also apply to ships over 400 GT. However, these measures do not apply to a number of different kinds of ships, including fishing vessels, tugs, waterbuses, pilot boats, etc. Armstrong claims [3] that smaller ships are responsible for 15–20% of the total greenhouse gas emissions. In other words, there is currently still a significant amount of CO_2 that is unregulated.

Pilot boats are vital for maritime safety, ensuring safe navigation of vessels entering and departing ports or navigating hazardous areas. Recognized by the IMO in 1968 through Resolution A.159 (ES.IV), pilotage is compulsory in most port areas and territorial waters [4]. Despite their importance, pilot boats have not been widely studied scientifically, particularly regarding their environmental impact [5,6]. Typically small, fast vessels designed for year-round operation in varying weather and sea states, pilot boats are predominantly powered by marine diesel oil, resulting in high fuel consumption and GHG emissions [7]. In addition, there are also formalities of reporting for ships arriving in and departing from ports of the EU's member states [8].

In Estonia, pilotage services are provided by 20 pilot boats across six regions and 30 ports. The unique operational challenges arise due to ice cover for three months each year, necessitating ice-capable vessels during the winter season. These vessels incur significantly higher operating and capital costs but are inefficient during ice-free periods, remaining idle for most of the year. Additionally, Estonian ports are located within the Baltic Sea Emission Control Areas (ECAs) under MARPOL Annex VI, increasing the urgency of using environmentally friendly fuels [9].

As the EU aims for decarbonization by 2050, pilot boats, despite their small size, must adapt to low-emission technologies. State-owned pilot fleets, including those in Estonia, have declared their commitment to becoming carbon-free [10–15]. The limited data on pilot boats and their emissions highlights the need for research into effective GHG reduction strategies tailored to their unique operational characteristics. While numerous studies in the literature compare the technical, safety, operational, and feasibility aspects of alternative fuels for use in the maritime sector, no studies in the literature specifically focus on pilot boats. Given the unique design and operational demands of pilot boats, they warrant detailed investigation to identify optimal strategies for reducing their emissions effectively.

This study addresses the research gap by evaluating the feasibility of alternative fuels for pilot boats by using the Estonian pilot fleet as a case. Using a Well-to-Wake (WtW) life cycle assessment (LCA) methodology and operational data from 18 vessels, the study compares the GHG emissions, efficiency, costs, and storage requirements of alternative fuels, including biomethane, hydrogen, ammonia, biodiesel, and hydrotreated vegetable oil (HVO). The findings aim to provide actionable insights into decarbonizing pilot boats in the Baltic Sea region. Our main question is: Which alternative fuel could be the most prospective to be used in the Estonian pilot boat fleet?

The literature review in Section 2 primarily focuses on fuel alternatives that are suitable for implementation on smaller ships. The research environment in Section 3 describes the current Estonian pilotage fleet, its capabilities, and its operational restrictions. The methodology section in Section 4 illustrates how fuel consumptions were assessed for different fuel alternatives and how the GHG emissions were calculated. The results section is merged with discussions in Section 5, which is divided into several sub-chapters: first, we show the actual GHG emissions of the fleet in 2023, then we show the results of potential fuel alternatives with their fuel consumptions, and finally, GHG emissions of the fuel alternatives are calculated based on the pilotage areas. The section also illustrates possible scenarios for the pilot fleet's future while considering the research results. The conclusion summarizes the research with proposals for the fleet to reduce their GHG emissions.

2. Literature Review

The FuelEU Maritime Regulation was adopted in July 2023 as part of the EU's Fit for 55 package [16]. The regulation promotes the use of renewable, low-carbon fuels and clean energy technologies for ships, which is essential to decarbonizing the maritime sector.

Maritime transport accounts for 3–4% of the EU's total CO_2 emissions [17]. To achieve significant and cost-effective reductions, the EU Emissions Trading System (EU ETS) was implemented in January 2024 [18]. The EU ETS applies to ships with a GT of 5000 or more that enter EU ports, regardless of their flag. Under this system, shipping companies are required to purchase and use EU ETS allowances for each ton of CO_2 emissions reported within this scope. This measure is essential to promote energy efficiency, encourage the adoption of low-carbon solutions, and reduce the cost disparity between alternative fuels and traditional marine fuels. It also drives shipping companies, shipowners, and industry developers to accelerate decarbonization efforts.

The decarbonization of shipping currently involves all stakeholders in the maritime sector. However, no single solution can address all the sector's needs [19]. Pilotage, while a small component of the shipping industry, plays a significant role in port management and infrastructure. Although pilot boats are not directly covered by the IMO GHG strategy, their owner governments often have local and national goals to reduce greenhouse gas emissions. Pilotage companies are closely monitoring advancements in shipbuilding and retrofitting. In recent years, there has been increasing interest in alternative fuels to minimize the environmental impact of pilotage operations. This chapter provides an overview of various alternative fuels that could be adopted for pilot boats, examining their benefits and challenges.

Biodiesel offers several environmental and operational advantages, including being biodegradable, non-toxic, and low in sulfur, which significantly reduces SO_x emissions compared to traditional marine fuels [20,21]. Its oxygen-rich composition enhances combustion efficiency, leading to lower particulate and CO_2 emissions, and it can be blended with diesel with minimal engine modifications [22,23]. However, the lower energy density of biodiesel can create up to a 20% increase in fuel consumption, negatively impacting both range and efficiency [21,23,24]. Its high viscosity and poor cold-flow properties require heating systems in colder climates [21,25]. Safety concerns include potential corrosion in certain materials and challenges with storage and transport. While generally producing lower NO_x emissions [20,21,23], some engine configurations may experience increases. In addition, biodiesel remains costlier than conventional fuels [26–28], and global infrastructure for its use in shipping is limited [20,21].

Methanol is a promising alternative fuel for the maritime sector due to its environmental benefits, such as significantly reduced SO_x, NO_x, and particulate matter emissions compared to traditional marine fuels [29–33]. When produced from renewable sources like biomass or captured CO_2, methanol can drastically cut greenhouse gas emissions, though natural gas-derived methanol still has a lower environmental footprint than coal-based options [31,33,34]. However, methanol faces challenges, including its low energy density, requiring larger storage tanks, and its toxicity and corrosiveness, which demand specialized handling and safety measures [31,35,36]. Its low flashpoint requires additional safety precautions, while its lower cetane number and higher auto-ignition temperature necessitate engine modifications or the use of dual-fuel systems [29,31,37]. Despite these challenges, methanol is easy to store and transport in liquid form at ambient conditions, and its clean-burning properties and scalability make it a viable option for complying with future environmental regulations [36,38,39].

Sweden has pioneered the use of methanol fuel in pilot boats. The Swedish Maritime Administration introduced the world's first methanol-fueled pilot boat, Pilot Boat

120 SE [40,41]. This vessel was repowered with an adapted Scania V8 diesel engine, offering diesel-like performance with a much more favorable emissions profile. Methanol, especially green methanol, is a promising alternative due to its minimal emissions (no particulate matter, sulfur oxides, and very low nitrogen oxides) and potential for zero net CO_2 emissions. Methanol is increasingly being explored as a marine fuel, including for deep-sea shipping, due to its ease of use and compatibility with existing engine technologies. However, its installation costs are approximately 5% higher than those of standard diesel engines.

Hydrotreated Vegetable Oil (HVO) is gaining recognition as a drop-in biofuel due to its chemical similarity to diesel, enabling compatibility with existing marine engines and infrastructure without significant modifications [36,42,43]. This makes it an appealing option for retrofitting fleets to comply with stricter environmental regulations. HVO is sulfur-free, produces lower particulate emissions, and offers significant reductions in lifecycle greenhouse gas emissions, particularly when sourced from waste oils [36,43,44]. However, challenges include its limited availability, high cost compared to fossil diesel, and underdeveloped global supply chains [35,36,43]. Despite having a higher energy density than LNG [36,43], its expense may deter adoption without regulatory or financial incentives [35,36]. On the positive side, HVO's high flashpoint enhances safety in storage and handling, and its non-toxic nature reduces environmental risks from spills [36,37]. In addition, it can be integrated with exhaust gas treatment systems to meet NO_x standards, though extra equipment might be required [45,46].

The Dublin Port Company conducted successful trials using HVO in their pilot boats [47]. According to them, the use of HVO fuel in the pilot boats indicated a significant reduction in CO_2 emissions (between 80 and 90%) without requiring any modifications to existing diesel engines. This approach aligns with broader goals to reduce carbon emissions and improve sustainability in maritime operations.

Biomethane derived from biomass sources like landfill gas recovery and anaerobic digestion offers significant advantages as a marine fuel [36,44,45]. It can greatly reduce GHG emissions by recycling carbon that would otherwise be released from decomposing organic matter [26,34,48]. Combustion of biomethane generates very low levels of SO_x and NO_x, ensuring compliance with stringent environmental regulations [31,49]. Additionally, biomethane benefits from logistical compatibility with LNG, utilizing the same supply chains and storage systems, which facilitates a seamless transition for operators already using LNG [26,36,45]. However, biomethane's scalability is limited by the availability of organic waste sources, constraining its widespread adoption [30,34]. Despite this, it remains highly viable for inland waterway and short-sea operations, especially in regions with established biomethane infrastructure. Challenges include the energy-intensive processes involved in its production, such as collection, purification, and transportation, as well as higher costs compared to fossil fuels [26,50]. From a safety perspective, biomethane is relatively secure, with a high autoignition temperature and low toxicity, but it requires storage at very low temperatures or in liquefied form, presenting operational challenges [26,34,36]. Additionally, methane leakage must be carefully managed due to its potent greenhouse gas effect. Biomethane's clean emissions profile and suitability for dual-fuel gas engines [51] further position it as a promising sustainable fuel for short-distance maritime applications.

Hydrogen is a promising alternative fuel for marine applications, offering zero emissions when produced from renewable sources, as it emits only water vapor in fuel cells, eliminating CO_2, NO_x, SO_x, and particulate matter emissions [29,34,52]. Abundant and scalable through water electrolysis powered by renewable energy, hydrogen presents a viable pathway for maritime decarbonization [29,30,35]. However, its adoption faces challenges, including storage and handling complexities due to its low volumetric energy density, requiring compression or cryogenic liquefaction, which increases cost and operational difficulty [29,34,36]. Safety concerns arise from hydrogen's high flammability, while its production cost, particularly for green hydrogen, remains a significant economic barrier [30,34,36]. Although hydrogen can power both fuel cells and adapted combustion engines, its low energy density limits its feasibility for short-sea shipping, and the underdeveloped bunkering infrastructure further restricts its widespread maritime use [30,52]. The main drawbacks are high costs and low gravimetric density, due to the high weights of the metal hybrid tanks: for this reason, they are suitable mainly for stationary applications and for some transportation applications only, such as submarines and small boats [53,54].

Green hydrogen has demonstrated its utility, for instance, in a crew transfer vessel [55], indicating its potential applicability for pilot boats as well.

Ammonia has emerged as a promising marine fuel due to its carbon-free combustion, eliminating CO_2, CO, and unburned hydrocarbon emissions, which aligns with international maritime decarbonization goals [29,34,35]. Its scalability is supported by existing infrastructure from the fertilizer industry, facilitating its production and transportation [36,56]. However, ammonia faces significant challenges, including a high auto-ignition temperature and low flame speed, which complicate combustion in conventional engines [36,37,57]. Its toxicity and corrosive properties necessitate specialized handling, storage, and engine modifications, while its lower energy density requires more storage volume than diesel [34,36,58]. Additionally, ammonia combustion may increase NO_x and N_2O emissions, requiring systems like selective catalytic reduction (SCR), which reduce efficiency due to increased exhaust backpressure [36,59,60]. Although "green" ammonia production using renewable energy could make it a completely carbon-free fuel, this technology remains costly and under development [34,56].

3. Research Environment

Pilotage is a mandatory service regulated by Estonia's Maritime Safety Law. As of 1 August 2023, the State Fleet of Estonia oversees the management of state vessels (excluding those registered to the Defense Forces and Defense League), the maintenance of floating navigational aids, the execution of icebreaking operations, and the provision and development of pilotage services in Estonia.

The pilot fleet currently comprises 18 vessels specifically designed for pilotage. These boats range from 12 to over 20 m in length and are built to endure challenging seas, various weather conditions, and contact with different types of vessels. They are high-powered, making them both fast and durable, with some boats equipped with advanced ice-crushing capabilities. Below, Table 1 provides an overview of the main characteristics of these vessels, and Table 2 shows the propulsion and performance characteristics of the fleet. In recent years, the total number of pilotages in Estonian waters has remained relatively constant, indicating a stable market (Figure 1).

Table 1. Main ship data of Estonian State Fleet pilot boats.

Ship	Ice Purpose	Home Port	Year Built	LOA [m]	BOA [m]	Draught [m]	Displacement [t]
AHTO-01	icebreaker	Muuga	2009	16	5.3	2.47	63.68
AHTO-02	icebreaker	Pärnu	2011	16	5.3	2.47	63.68
AHTO-06	ice-capable—10 cm	Kunda	2002	13.5	4.56	1.6	14.6
AHTO-07	icebreaker	moving ports	2014	16	5.3	2.43	63.68
AHTO-09	icebreaker	Roomassaare	2014	16	5.3	2.43	63.68
AHTO-12	depreciated	Kunda	1966	12.5	3.95	1.5	22.6
AHTO-14	summer	Heltermaa	2015	14.22	4.5	0.83	21.4

Table 1. *Cont.*

Ship	Ice Purpose	Home Port	Year Built	LOA [m]	BOA [m]	Draught [m]	Displacement [t]
AHTO-15	summer	moving ports	2015	18.37	5.1	1.6	35.5
AHTO-17	ice-capable—10 cm	Roomassaare	2003	13.5	4.55	1.61	14.6
AHTO-19	ice-capable—10 cm	Virtsu	2003	14.1	4.56	1.61	15.7
AHTO-20	ice-capable—10 cm	Pärnu	2003	14.1	4.46	1.61	16
AHTO-21	ice-capable—10 cm	Heltermaa	2004	14.1	4.56	1.61	16
AHTO-23	ice-capable—10 cm	moving ports	2004	14.1	4.56	1.61	16
AHTO-25	ice-capable—15 cm	Muuga	2006	19.5	5.45	1.85	36.4
AHTO-26	ice-capable—15 cm	Meeruse	2007	19.5	5.45	1.85	35.8
AHTO-27	ice-capable—15 cm	Paldiski	2008	19.5	5.45	1.85	35.8
AHTO-28	ice-capable—15 cm	Rohuneeme	2008	19.5	5.45	1.85	35.8
AHTO-29	summer	moving ports	2010	17.6	5.4	1.4	25

Table 2. Propulsion and performance characteristics of the fleet.

Ship	Avg. Fuel Consumption [L/Mile]	Fuel Capacity [m^3]	Max Speed [kn]	Avg Speed [kn]	Engine Power [kW]	Engine Model
AHTO 01-02-07-09	11.61	6.3	10.4	7.8	852	DG SCANIA DI16
AHTO 06-17-19-20-21-23	4.88	1.1	22	19.8	525	MTU 8V2000M70
AHTO 12	2	2.76	8	4.6	162	IVECO
AHTO 14	5.97	1.6	27	25.6	736	Volvo-Penta D13
AHTO 15	6.18	3.0	27	22.8	958	Volvo-Penta D16
AHTO 25-26-27-28	7.79	5.5	22	19.4	900	MTU 10V2000M72
AHTO 29	7.02	4.0	35	30.6	1176	Volvo-Penta IPS 1050

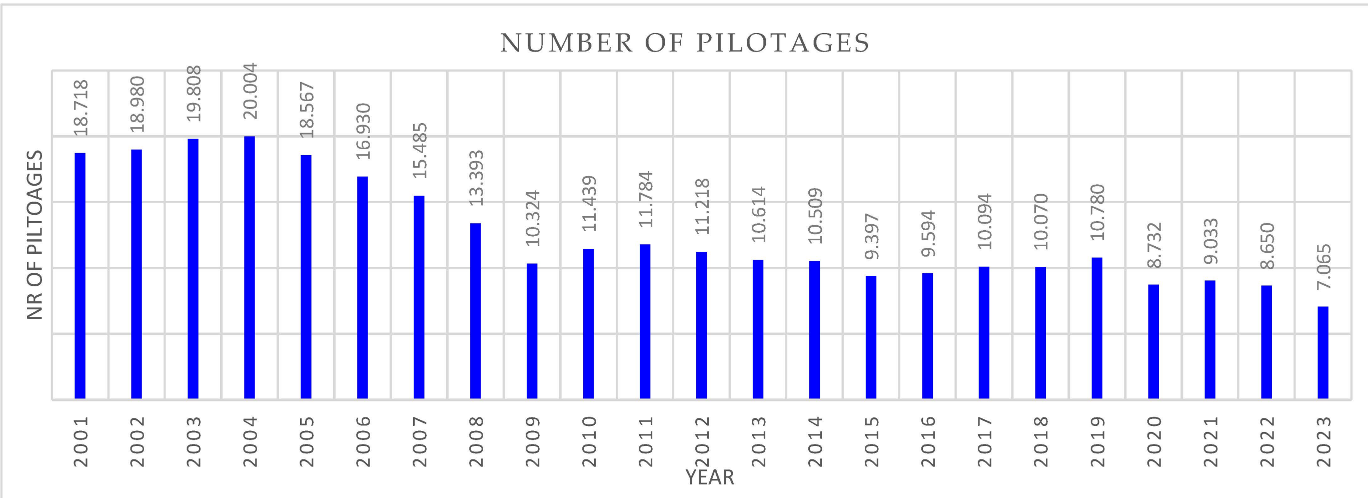

Figure 1. Yearly number of pilotages.

The coastline and pilotage conditions in Estonia, despite being a small country, are diverse. Variations occur in the number of pilotage operations per station and the average distances covered, influenced by trade flow and seasonal changes (Table 3). Based on the geographical distribution of Estonia's ports and primary trade routes, the country is divided into six distinct pilotage areas: Kunda-Loksa, Paldiski, Pärnu, Tallinn, Väinameri, and Sillamäe (Figure 2).

Table 3. Average pilotage data for 2023.

Area	Boat	Distance Max nm		Maximum Number Pilotages in 24 h	Total Distance of Pilotage in 24 h
	Location	Winter	Summer	Pcs	m
Kunda/Loksa	Kunda	7	13	8	60
Paldiski	Paldiski	8	8	11	90
Pärnu	Pärnu	3	7	9	65
Tallinn/Muuga	Meeruse	8	8	5	40
	Hundipea	20	20	15	150
	Muuga	20	20	14	160
Väinameri	Roomassaare	12	12	3	36
	Virtsu	30	30	3	50
	Heltermaa	30	30	3	50
	Veere	0	20	1	20

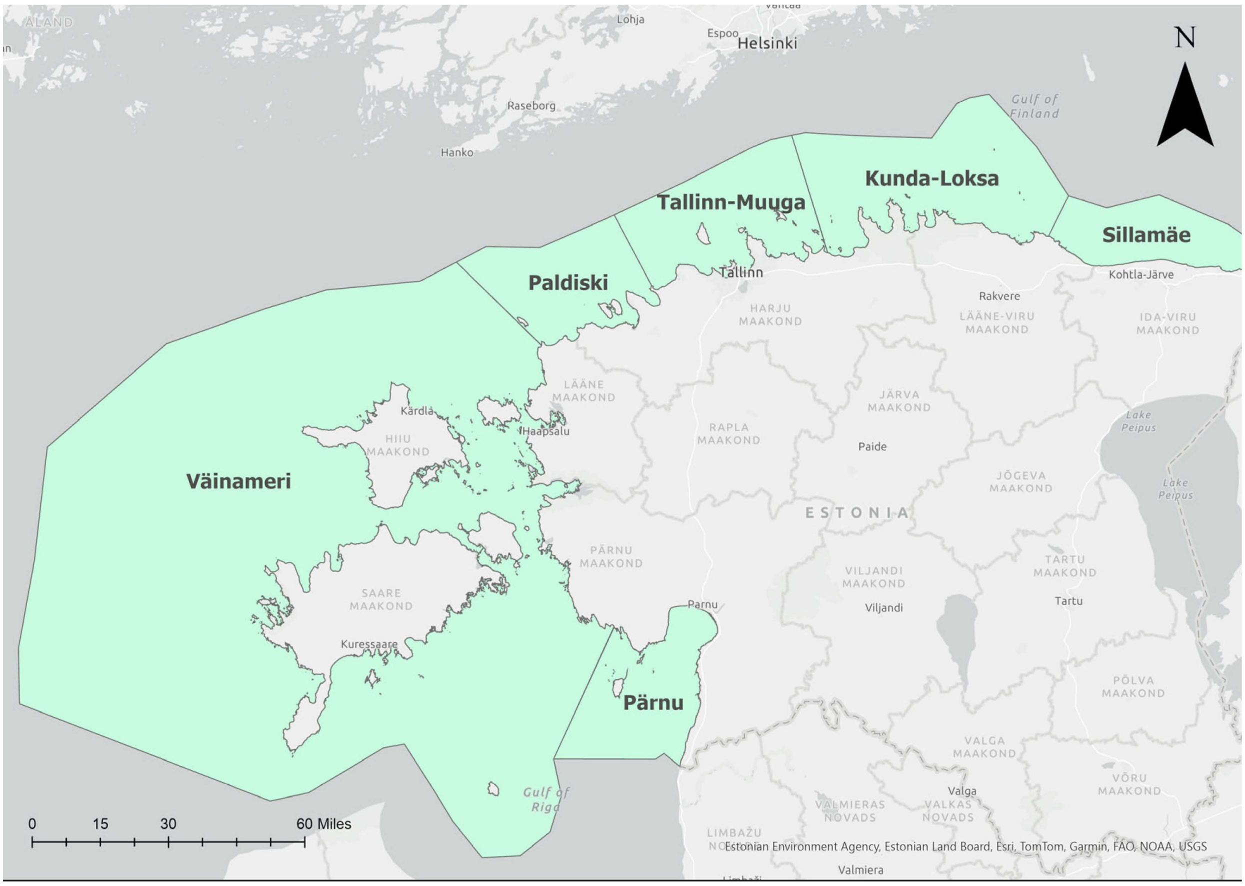

Figure 2. Estonian pilotage areas.

The current fleet of pilot boats in Estonia predominantly consists of vessels powered by diesel engines, reflecting the traditional approach to maritime operations. However, there is a growing interest in exploring more sustainable and diverse energy sources for future upgrades. While the current fleet has not yet adopted alternative propulsion systems, such as hybrid or electric engines, discussions are underway to consider these options as part of broader efforts to reduce emissions and enhance environmental sustainability in pilotage services.

4. Methodology

4.1. Data Collection and Calculation

This study aimed to evaluate the most promising alternative fuel options for the Estonian State Fleet pilot boats, considering technical feasibility, environmental impact, and economic considerations. The first step involved collecting data on current fuel consumption, average and the peak daily mileage, and other relevant specifications for each vessel in the fleet. Additional technical parameters, such as maximum speed, maximum power, and average operational speed, were also gathered. These details enabled precise calculations of engine performance and fuel requirements. Furthermore, the brake-specific fuel consumption (BSFC) for each engine model at both the maximum power and 50% partial power was obtained from technical specification catalogs [61–66].

Next, the peak daily mileage for each vessel was determined using daily mileage data to assess high-use operational demands. To estimate engine load at average speeds, the propeller law was applied, where engine load is calculated as a function of the cube of the speed ratio. Power at average speed was calculated by multiplying the maximum power by the cube of the ratio of average speed to maximum speed, providing a baseline for typical power consumption under standard operating conditions. The methodology of the propeller law is illustrated in Equations (1) and (2) [67]. As the Propeller Law is based on the relationship between shaft speed and engine load, and some experimental studies in the literature [68–70] confirm the existence of this relationship for small-sized engines, this method is also applicable to pilot boats under constant speed scenarios. Since average fuel consumption for each vessel was known but operational engine load was not, Equations (3) and (4) were used to estimate engine load. Given that BSFC varies with engine load, these equations facilitated the estimation of operational engine load through an iterative approach.

$$P_{max} = \frac{FC_{max}}{BSFC_{max}} \tag{1}$$

$$P_{avg} = P_{max}\left(\frac{v_{avg}}{v_{max}}\right)^{\frac{1}{3}} \tag{2}$$

$$BSFC_{avg,sp} = BSFC_{50\%} + (BSFC_{max} + BSFC_{50\%})\left(\frac{P_{avg}}{P_{max}} - 0.5\right) \tag{3}$$

$$FC_{avg,sp} = BSFC_{avg,sp} \, * \, P_{avg} \tag{4}$$

In Equation (1), P_{max} is the maximum power output (kW) calculated by dividing the maximum fuel consumption rate FC_{max} (kW) by the brake-specific fuel consumption at the maximum load $BSFC_{max}$ (kg/(kWh)). Equation (2) gives, P_{avg} the power needed at the average speed, calculated by scaling P_{max} by the cube of the ratio of the average to maximum speed ($\frac{v_{avg}}{v_{max}}$). Equation (3) estimates the average BSFC for a specific engine load ($BSFC_{avg,sp}$) and also the average engine load ($\frac{P_{avg}}{P_{max}}$) by interpolating between the BSFC values at 50% load and the maximum load ($BSFC_i$), adjusted by the load factor ($\frac{P_{avg}}{P_{max}} - 0.5$).

The peak energy need between bunkering operations and peak daily working hours of the vessels were other important parameters for determining the fuel tanks' capacities. The vessel capacities for each fuel type were key factors in comparing fuel alternatives, considering tank volume and fuel weight. For this purpose the maximum daily fuel consumption data were derived from the monthly fuel consumption data of each ship by the following formula where t_{bb} is the time (days) between bunkering and $FC_{daily,\ peak}$ is the daily average fuel consumption in the month in which the maximum fuel consumption for that ship was performed.

Fuel tank capacities for each type were determined by peak energy demand, full tank capacity, and daily operating hours $\left(h_{daily}\right)$. To estimate this, the maximum daily fuel consumption ($FC_{daily,\ peak}$) was calculated by averaging from monthly fuel consumption data for each ship that was used in the following formulas. In this formula, t_{bb} represents the time (in days) between bunkering (converted to hour for calculations), $FC_{daily,\ peak}$, is the daily average fuel consumption during the month when the vessel recorded its highest fuel consumption and FC_{avg} is the average fuel consumption of the vessel in average speed.

$$E_{tank,peak} = t_{bb}\frac{FC_{daily,peak}}{BSFC_{avg}} \tag{5}$$

$$h_{daily} = \frac{FC_{daily,peak}}{v_{avg}FC_{avg}} \tag{6}$$

The size of fuel tanks and the weight of the necessary fuel between bunkering operations serve as performance indicators for alternative fuels. Each fuel type varies in density and calorific value. Since pilot boats do not carry cargo, the weight and volume impact of alternative fuels is more pronounced compared to cargo ships. Since pilot boats are relatively small, the extra fuel weight or volume could lead to design challenges, potentially exceeding design weight and volume limits. These changes in weight and volume affect crucially the vessel's stability and metacentric height, especially during contact with other vessels. A critical change in metacentric height while the pilot boat is moving at high speed can lead to capsizing.

This study examines weight and volume costs through two scenarios. In the first scenario, the boats' original range with marine diesel oil (MDO) was maintained, so the alternative fuel capacity after retrofitting matched this range. In the second scenario, the range was adjusted based on the ships' past service times. These scenarios assess operational range preservation and adaptation to real-world usage, ensuring practical evaluation of alternative fuels. Both scenarios calculated weight costs, considering the relative power-to-weight ratio of the engines or motors and the weight of fuels. An assumption was made that after the retrofit, the ships would maintain the same propulsion power in both scenarios. For both scenarios, the relative weight and relative volume of each fuel were calculated first. These are the relative weights and volumes of alternative fuels to give the same energy amount theoretically.

$$m_{rel,i} = \frac{Q_{MDO}}{Q_i} \tag{7}$$

$$V_{rel,i} = \left(\frac{Q_{MDO}}{\rho_{MDO}}\right) / \left(\frac{Q_i}{\rho_i}\right) \tag{8}$$

Here, m_{rel} and V_{rel} are relative mass and volume of each fuel, Q_{MDO} and Q_i are calorific value of MDO and alternative fuels, and ρ_{MDO} and ρ_i are the density of MDO and alternative fuels.

In Scenario 1, the relative weight and volume costs of alternative fuels were calculated using specific equations. In these equations the relative weight and volume costs of alternative fuels were calculated for the same operation range, with the original fuel tank capacity in vessels.

$$m_{rel,cost,1} = \frac{P_b \times PWR_i + m_{rel,i} \times V_{fuel} \cdot \rho_{MDO} / \mu_i}{P_b \times PWR_{MDO} + V_{fuel} \times \rho_{MDO} / \mu_{MDO}} \tag{9}$$

$$V_{rel,cost,1,2} = V_{rel,i} \frac{\mu_{MDO}}{\mu_i} \tag{10}$$

where P_b is the brake power of the engine, PWR is the power to weight ratio for each propulsion system, V_{fuel} is the fuel tank capacity of the current ship design with MDO as fuel and μ_{MDO} and μ_i are brake thermal efficiency of MDO and alternative fuels.

In Scenario 2, the relative weight and volume costs of alternative fuels were determined based on optimized operation ranges derived from each vessel's service time. As the relative volume cost is unaffected by engine weight, the same method applies to both scenarios. While the volume costs of fuels may differ between scenarios, the relative rates remain consistent.

$$m_{rel,cost,2} = \frac{P_b \times PWR_i + m_{rel,i} \times \frac{E_{tank,peak}}{(Q_i \cdot \mu_i)}}{P_b \times PWR_{MDO} + \frac{E_{tank,peak}}{(Q_{MDO} \times \mu_{MDO})}} \tag{11}$$

Equations (9) and (11) were developed based on fundamental engineering principles to estimate the relative weight and volume costs of alternative fuels compared to MDO. Key parameters such as engine power, power to weight ratio, fuel tank capacity and brake thermal efficiency are considered in these equations. While Equation (9) assumes the same fuel tank capacity as currently used for MDO, Equation (11) incorporates energy requirements for peak operational scenarios. These equations have been specifically tailored to the operational characteristics of the fleet, providing a robust framework for evaluating fuel alternatives in this context.

The yearly fuel consumption for each vessel with each alternative fuel was calculated using Equation (12). This equation estimated the annual fuel consumption for each fuel type based on the vessels' previous service times.

$$FC_i = \frac{m_{rel,i} \times \mu_{MDO} \times FC_{MDO}}{\mu_i} \tag{12}$$

The OpEx (operational expenses) for each ship is a key performance indicator for evaluating alternative fuels. Although factors such as maintenance costs, amortization time, and service costs also impact operational costs, they require extensive data that is currently unavailable in the literature. Therefore, only the primary cost of operation—the fuel cost—is considered in calculating the operational costs. These costs are calculated using Equation (13).

$$OpEx_i = FC_i \times UC_i \tag{13}$$

Here, $OpEx_i$ indicates the yearly operational cost with each fuel and UC_i indicates the unit cost of each fuel in the Eastern European market.

Figure 3 provides a visual representation of the calculations. In the figure, the data sources are distinguished by color: yellow represents data collected from the Estonian State Fleet, blue denotes data obtained from engine producers' datasheets and instruction manuals, orange indicates data gathered from the literature, and purple signifies calculated or predicted values.

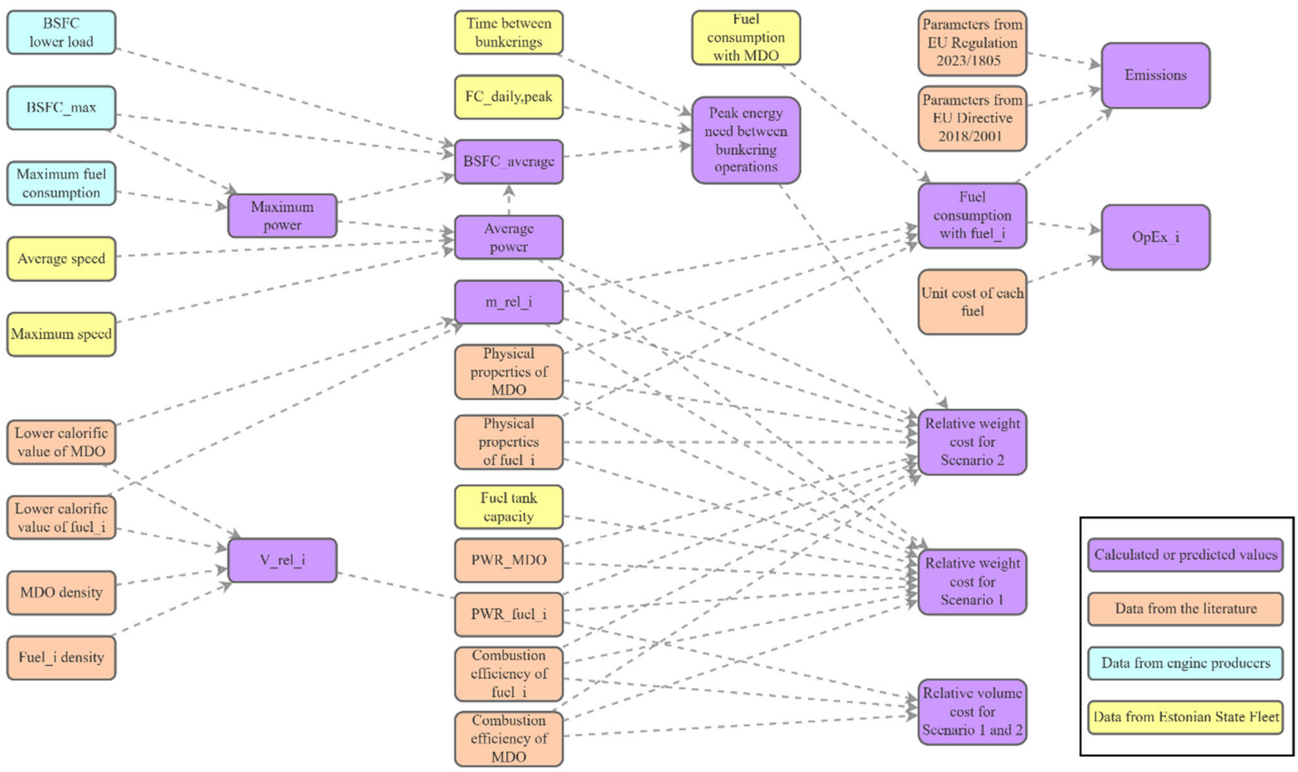

Figure 3. Flow diagram for calculations and predictions.

4.2. Fleet Performance and Alternative Fuels

Table 4 presents the brake-specific fuel consumption (BSFC) values for each vessel in the Estonian State Fleet. BSFC measures the fuel consumption per unit of power produced by an engine, typically expressed in grams of fuel per kilowatt-hour (g/kWh). These values were used to calculate the BSFC for each ship at specific engine loads. The data were sourced from the technical datasheets of each engine model, as provided by the manufacturers [61–66]. The BSFC at full load represents fuel consumption at maximum power output, reflecting the engine's efficiency at its highest load. However, ships typically operate at operating loads, defined as the percentage of maximum engine capacity utilized during regular operations. These operating loads were predicted using Equation (2) by applying the "Propeller Law" specifically to each ship in the fleet. While manufacturers provided BSFC data for reduced power outputs under varying engine speeds and lower load scenarios—representing load conditions chosen by the manufacturer—these lower loads do not align with the actual operating loads. Therefore, BSFC at operating loads was calculated using a linear regression-based method, as outlined in Equation (3). This method adjusts the formula to account for the power ratio between lower and full load, enabling an accurate prediction of BSFC under typical operating conditions.

Weight costs, volume costs, fuel consumption, and operational costs were calculated based on the operational ranges of each vessel. Key parameters include the energy needs of each vessel between bunkering intervals (which impacts the required fuel quantity on board) and peak working hours per day, as retrofitted ships must meet the operational demands of each vessel. Figure 4a,b illustrate each vessel's energy needs between bunkering operations, assumed to occur every 10 days, and the daily average working hours. It is important to note that energy needs and working hours vary across different months and operational conditions, and the values in the figures represent peak time conditions.

Table 4. BSFC values for the fleet at full load and lower loads.

	Full Load			Lower Load		
	BSFC	Rpm	Rated Power	BSFC	Rpm	Rated Power
	g/kWh		kW	g/kWh		kW
AHTO 01-02-07-09	213	1800	468	205	1500	445
AHTO 06-17-19-20-21-23	214	2250	720	205	1950	475
AHTO 12	220	2800	184	215	1400	92
AHTO 14	216	2400	735	206	1900	400
AHTO 15	210	1800	479	200	1200	400
AHTO 25-26-27-28	213	2250	900	211	1950	585
AHTO 29	212	2300	564	201	1400	185

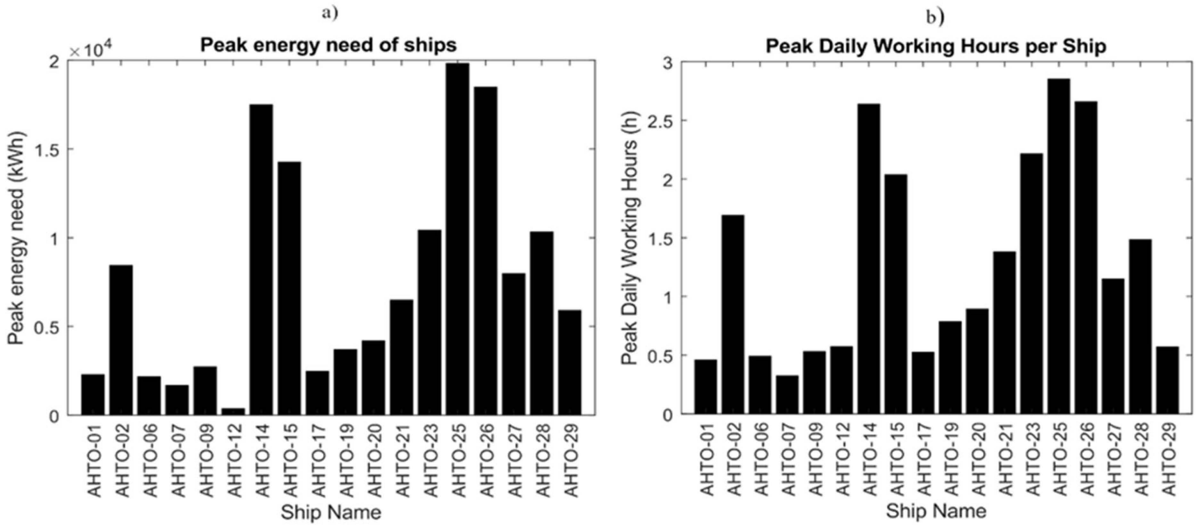

Figure 4. (**a**) Peak energy needs of the ships between bunkering operations; (**b**) peak daily working hours of the ships.

The peak energy requirements of the vessels vary significantly, ranging from 364 kWh to 19,800 kWh. These values represent the average energy demand of each vessel under peak operational conditions over a 10-day period. This indicates that if these energy needs can be met through alternative fuels and bunkering operations are conducted every 10 days, the vessels can operate without problems, even during peak scenarios. To analyze operability, the weight and volume costs for each alternative fuel, as well as for electric and hybrid propulsion options, were calculated under two scenarios. In the first scenario, the fuel quantity was determined to match the design range of each vessel. In the second scenario, the quantity was calculated to meet the energy needs for peak conditions, assuming a 10-day interval between bunkering operations. In addition, Figure 4b illustrates the peak daily working hours of the vessels, which vary from an average of 0.32 h to 2.85 h per day. This indicates that, even during peak operation, the vessels in the fleet are used for only a small portion of the day. This suggests that the current fuel tank sizes may be larger than necessary to meet the vessels' operational requirements.

Table 5 presents the physical and combustion properties of various fuels. Each fuel in the study was evaluated based on its energy density, volumetric density, required engine weight, combustion efficiency, and operational expenditures. These values in the table were used for the calculations for each fuel.

Table 5. The properties of various fuels *.

	Lower Heating Value	Density	Relative Engine Gravimetric Energy Density	Fuel Cost	Relative Thermal Efficiency
	(MJ/kg)	(t/m^3)		(€/ton)	
MDO	42.7 [49,71,72]	0.84 [49]	1	672 [73]	1
Methanol	19.9 [49,71,72]	0.79 [49]	0.78 [74]	381 [75–78]	1.03 [72,79]
Biodiesel	37.5 [21,80,81]	0.88 [21,81,82]	1	1127 [73]	0.96 [21,80]
HVO100	44.1 [82–84]	0.78 [83–85]	1	1456 [73]	0.99 [82,86–89]
H_2 (SOFC)	120 [49,71,72]	0.023 * [49]	0.65 [90–95]	5000 [96,97]	1.3 [74,98]
H_2 (PEMFC)	120 [49,71,72]	0.021 * [49]	1.01 [90–95]	5000 [96,97]	1.21 [74,91,99]
Ammonia	18.6 [71,72,85,100,101]	0.68 [90,98]	0.78 [74,102]	590 [73]	1.03 [102–105]
Biomethane	36 [103,106]	0.25 * [92–94]	0.89 [107]	1150 [78,108]	1.04 [109,110]

* (at 300 bar, −15 °C).

For each fuel type, we estimated fuel consumption, operational costs, and exhaust emissions (Figure 5). The lower heating value and density of fuels, as well as their fundamental physical properties, were sourced from widely available references. Many alternative fuels, such as hydrogen, ammonia, HVO100, and methanol, are already commercially available for various applications, with some suitable for bunkering on marine vessels. Other fuels are also used across different industries. Fuel costs were obtained from global market data, focusing on prices in Estonia and neighboring European countries (Table 5). While there is considerable interest in these fuels within experimental and academic research, and some compatible engine models exist, there remains a lack of suitable engines that meet the power demands of the pilot boats analyzed in this study. Although smaller engines compatible with these fuels are expected to be developed soon, comprehensive data on their gravimetric energy density and combustion efficiency are currently unavailable. In this study, gravimetric energy density was estimated using instruction manuals for engines of various sizes. It was observed that as the lower heating value of a fuel decreases, the gravimetric energy density of the engine also declines. Fuels with lower heating values require larger engines due to the need for increased cylinder sizes. Relative efficiency values were derived from experimental studies comparing the combustion performance of alternative fuels in internal combustion engines, using diesel oil as the reference fuel.

4.3. Assessing Shipping Emissions

In July 2023, the FuelEU Maritime Regulation was adopted [111] with the aim to support decarbonization of the shipping sector by promoting the use of renewable, low-carbon fuels, and clean energy technologies for ships. In shipping, there are various methods to calculate emissions [112], and although several research studies [113–117] and proposals [118–123] have been conducted, there is still an open debate about the uniform methodology.

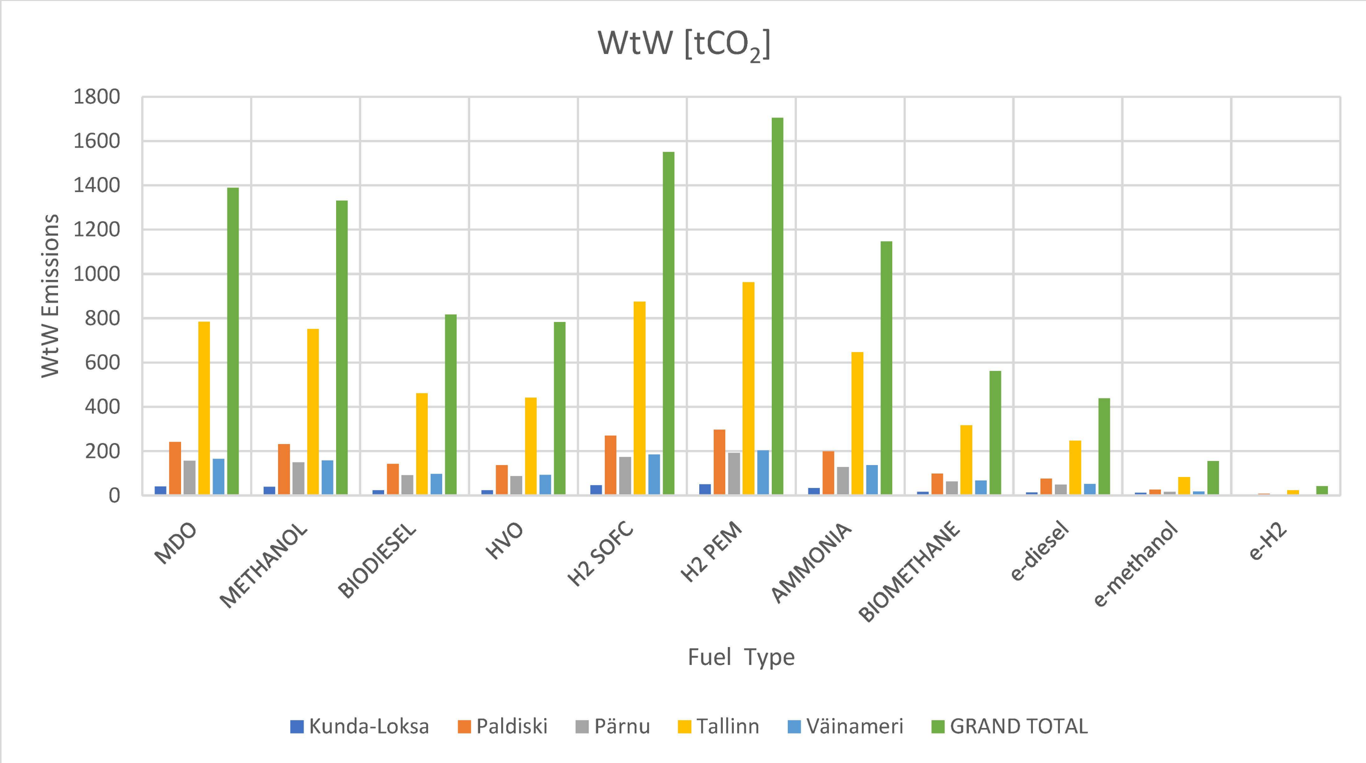

Figure 5. GHG emissions of the fuel alternatives by pilotage areas.

The life cycle assessment (LCA) is a comprehensive methodology used within the shipping industry to conduct a thorough evaluation of ecological impact while also considering the energy and emissions involved in constructing facilities, vehicles, or end-of-life aspects [124,125]. WtW GHG emissions are indicated as a subset of LCA, focusing specifically on fuel-related emissions.

The methodology for the current research [126] was derived from the geographical location and legislation. According to the suggestion of the IMO's Marine Environment Protection Committee (MEPC 77) life cycle guidelines, the GHG emissions should be estimated based on a Well-to-Wake method. The guidelines are proposed to be based on the sustainability and GHG emissions-saving criteria to incentivize the uptake of sustainable alternative fuels at the global level. The targets cover CO_2, methane, and nitrous oxide emissions over the full lifecycle of the fuels used onboard on a WtW basis. Therefore, this research focuses on the fleet's WtW GHG emissions.

Life cycle guidelines to estimate WtW GHG emissions are proposed by the EU [126] and IMO [127]. These suggested life cycle guidelines are based on sustainability and GHG emissions-saving criteria to incentivize the uptake of sustainable alternative fuels at the global level. The total GHG emissions include the Well-to-Tank (WtT) emissions of the energy carrier supply and the Tank-to-Wake (TtW) emissions of the total fuel use.

$$WtW_{GHG} = WtT(energy\ carrier\ supply) + TtW(fuel\ use) \tag{14}$$

The initial GHG assessment was calculated over a reference period of one year based on the collected data of actual fuel consumptions. The default emission factors that were used for the determination of the GHG intensity were established in accordance with the methodologies laid down in Directive (EU) 2018/2001 and Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC).

The total emissions depend on the fuel type and specifics. They are calculated by the following equation:

$$WtW_{GHG} = \sum_{i}^{n\ fuel} M_i \times CO_{2\ eq\ WtT,i} \times LCV_i + \sum_{i}^{n\ fuel} \sum_{j}^{m\ consumer} M_{ij} \times \left[(1 - C_{slip\ j}) \times (CO_{2\ eq,TtW}) + (C_{slip\ j} \times GWP_{CH4}) \right] \quad (15)$$

In this equation, i is the index corresponding to the fuels (for each specific fuel pathway) delivered to the ship over a reference period; j is the index corresponding to the different fuel consumers. The energy consumers considered are main engines, auxiliary engines, boilers, waste incineration plants, etc. k is the index corresponding to the connection points (c) where electricity was supplied per connection point. m is the index corresponding to the number of energy consumers. M_{ij} represents the mass of the specific fuel i oxidized in consumer j (in gFuel). $CO_{2eqWtT,i}$ are the WtT GHG emissions in gCO_2eq/MJ for each specific fuel, calculated according to an agreed methodology. $CO_{2eqTtW,I}$ are the TtW GHG emissions for in gCO_2eq/g Fuel for each specific fuel, when consumed on board by the fuel consumer j. $CO_2eqTtW, i = \left(C_{fCO2} \times GWP_{CO2} + C_{fCH4} \times GWP_{CH4} + C_{fN2O} \times GWP_{N2O} \right)_i$. C_{fCO2}, C_{fN2O}, C_{fCH4} are the emission factors in g of GHG/f of fuel. LCV_i represents the lower calorific value of the i fuel (considered in its own specific pathway) in MJ/g. $C_{slip\ j}$ represents fuel carbon slip in % of the mass of the fuel used by the energy converter j.

5. Results

5.1. Initial GHG Emissions

The initial GHG assessment, based on 2023 fuel consumption data from Estonian pilotage areas, calculated total emissions over a one-year reference period. The results for marine diesel oil are shown in Table 6.

Table 6. WtT, TtW, and WtW. emissions for Estonian pilotage areas in 2023, compiled by the authors based on actual fuel consumption data.

Pilotage Area	WtT Emissions	TtW Emissions	WtW Emissions	WtW Emissions
	[$kgCO_2eq$]	[$kgCO_2eq$]	[$kgCO_2eq$]	[tCO_2eq]
Kunda-Loksa	6592	34,895	41,486	41.5
Paldiski	26,860	142,195	169,055	169.1
Pärnu	25,563	135,325	160,888	160.9
Tallinn	109,656	580,503	690,159	690.2
Väinameri	47,086	249,266	296,352	296.4
TOTAL	215,756	1,142,185	1,357,940	1357.9

The calculation results show that the Tallinn pilotage area has the highest emissions, primarily due to its large ports and heavy sea traffic. The Väinameri area follows, which can be attributed to its complex operational patterns and extended pilotage distances.

5.2. Weight and Volume

Table 7 presents the comparative weight costs for each vessel in the fleet, with fuel quantities calculated to provide the same operational range as the original ship design. These values were calculated using Equation (9) and the parameters defined within it. The gravimetric density of alternative engines or fuel cells was also considered. This added weight is a significant factor for large ships, such as cargo or passenger carriers, as increased fuel weight reduces total cargo capacity. However, cargo vessels can offset this by adjusting cargo quantity to accommodate higher fuel weight. However, for pilot boats, additional fuel weight poses a more critical challenge due to their hull design and limited carrying capacity, which is optimized for lighter loads. This increased weight could exceed safety margins in hull design.

Table 7. Comparative weight * costs of the entire fleet using alternative fuels within the same design range.

	MDO	Methanol	Biodiesel	HVO100	H_2 Blue SOFC	H_2 Blue PEM	Ammonia	Biomethane
AHTO 01-02-07-09	1	1.74	1.11	0.98	0.77	0.57	1.83	1.13
AHTO 06-17-19-20-21-23	1	1.51	1.06	0.99	1.15	0.78	1.55	1.12
AHTO 12	1	1.88	1.15	0.98	0.55	0.45	1.99	1.13
AHTO 14	1	1.51	1.06	0.99	1.14	0.77	1.56	1.13
AHTO 15	1	1.58	1.07	0.99	1.04	0.71	1.63	1.13
AHTO 25-26-27-28	1	1.71	1.11	0.98	0.83	0.60	1.79	1.13
AHTO 29	1	1.59	1.08	0.99	1.01	0.70	1.65	1.13

* These options are calculated to meet a daily operation requirement of 4 h.

The findings show that methanol and ammonia lead to particularly high weight costs among alternative fuels. Despite strong industry interest in these fuels as alternatives to conventional options, their weight costs may render them less suitable for smaller vessels like pilot boats, especially when required to maintain the same range as the original design. However, operational adjustments—such as reducing tank size, thereby limiting range but allowing more frequent refueling— which can make these fuels viable alternatives.

The table also highlights that HVO100 and hydrogen reduce fuel weight costs relative to conventional diesel, while biomethane and biodiesel show a slight increase. It is essential to note that although the relative fuel weights remain constant across fuels, this study includes the weight costs of both the fuel and the engines required for each alternative fuel. Different fuels necessitate various engine types or fuel cells, each with unique gravimetric energy densities, and the fleet itself comprises vessels with diverse engine power capacities, contributing to weight cost variations even for the same fuel.

Like weight cost, volume cost is also a critical performance indicator for alternative fuels. While volume cost may be manageable for cargo vessels, it poses a greater challenge for smaller ships, such as pilot boats, due to their limited onboard space. Table 8 presents the volume requirements for various alternative fuels to achieve the same range as the original design. For MDO, this volume requirement matches the original tank capacity. These values were calculated using Equation (10) and the parameters defined within it.

Table 8. Tank volume needed [m^3] for the entire fleet using alternative fuels within the same range.

	MDO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO 01-02-07-09	5.3	11.8	6.2	5.6	5.3	5.7	16.1	18.0
AHTO 06-17-19-20-21-23	0.9	2.1	1.1	0.9	9.3	10.0	2.8	3.1
AHTO 12	2.3	5.2	2.7	2.5	23.3	25.0	7.1	7.9
AHTO 14	1.3	3.0	1.6	1.4	13.5	14.5	4.1	4.6
AHTO 15	2.5	5.6	2.9	2.7	25.4	27.2	7.7	8.6
AHTO 25-26-27-28	4.6	10.3	5.4	4.9	46.5	49.8	14.1	15.7
AHTO 29	3.4	7.5	3.9	3.6	33.8	36.2	10.3	11.4

The findings suggest that biodiesel and HVO100 have acceptable volume costs; biodiesel requires a slight increase in tank capacity, while HVO100 actually reduces the necessary tank size. Additionally, liquid fuels like methanol, biodiesel, HVO100, and ammonia can utilize existing tanks with retrofitting, thereby lowering the retrofit capital cost. However, to match the original design range, methanol and ammonia require significantly larger tank volumes relative to MDO. Due to space limitations on pilot boats, these fuels may not be ideal alternatives when the goal is to maintain the same range. Biomethane and hydrogen, due to their gaseous form, also present high volume costs. It should also be noted that the storage conditions of the fuels calculated are −15 °C and 25 MPa. But liquified storage can also be an option which will decrease the volume cost considerably. Typically stored on deck, these tanks consume valuable deck space and, being located higher than bottom tanks, increase the vessel's GC (gravity center), potentially compromising safety margins.

Overall, as can be seen in Tables 7 and 8, both weight and volume cost analyses indicate that only biodiesel and HVO100 appear promising as alternative fuels to MDO if the same range is expected post-retrofit. However, reducing the operational range of vessels post-retrofit to lower onboard fuel weight and volume could be a viable option. Therefore, reviewing each vessel's operational history and performing alternative calculations to meet peak fuel requirements during high-demand periods could yield useful insights. If fuel capacity is optimized for peak requirements, a new perspective on alternative fuel feasibility could emerge. For this purpose, Tables 9 and 10 show the weight and volume costs of alternative fuels and propulsion units for an optimized range, calculated to cover peak energy demands for each vessel by using Equations (10) and (11), allowing for operations up to 10 days without refueling. Shortening bunkering intervals further would reduce both weight and volume costs.

Table 9. Relative weight costs * of the entire fleet using alternative fuels within an optimized range (Comparing to design MDO tank capacity).

	MDO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO-01	0.46	0.62	0.47	0.45	0.62	0.41	0.63	0.51
AHTO-02	0.60	0.93	0.64	0.60	0.67	0.45	0.96	0.68
AHTO-06	0.85	1.20	0.88	0.85	1.11	0.73	1.22	0.96
AHTO-07	0.44	0.59	0.45	0.44	0.62	0.41	0.60	0.49
AHTO-09	0.47	0.65	0.48	0.46	0.63	0.41	0.65	0.52
AHTO-12	0.25	0.34	0.26	0.25	0.35	0.23	0.34	0.28
AHTO-14	1.54	2.63	1.70	1.51	1.29	0.93	2.75	1.74
AHTO-15	1.08	1.74	1.17	1.07	1.06	0.74	1.81	1.22
AHTO-17	0.87	1.24	0.90	0.87	1.12	0.74	1.27	0.98
AHTO-19	0.96	1.42	1.00	0.95	1.14	0.76	1.45	1.07
AHTO-20	0.99	1.49	1.05	0.98	1.15	0.77	1.53	1.11
AHTO-21	1.15	1.81	1.23	1.13	1.19	0.82	1.87	1.29
AHTO-23	1.42	2.37	1.55	1.40	1.26	0.90	2.47	1.60
AHTO-25	0.95	1.61	1.05	0.94	0.82	0.59	1.68	1.08
AHTO-26	0.92	1.54	1.01	0.90	0.81	0.58	1.61	1.04
AHTO-27	0.65	0.99	0.69	0.64	0.74	0.50	1.02	0.73
AHTO-28	0.71	1.11	0.76	0.70	0.75	0.52	1.15	0.80
AHTO-29	0.74	1.07	0.77	0.74	0.94	0.63	1.09	0.84

* These options are calculated to meet the one-day operation requirement at peak times.

Table 9 presents the weight costs of alternative fuels and propulsion units optimized to meet peak energy demands for 10 days without refueling. Interestingly, for vessels Ahto 14, Ahto 15, Ahto 21, and Ahto 23, the MDO requirements exceed the original design fuel capacity. This is due to the selected 10-day bunkering interval, implying that under peak demand conditions, these vessels cannot operate for 10 days without refueling using their original tank capacities. Peak demand scenarios, reflecting each pilot boat's unique operational patterns, show significant variation across vessels—while Ahto 12 experiences minimal peak-time usage, Ahto 14 has much higher operational frequency. The results demonstrate that all fuels, both liquid and gas, can meet peak energy demands at an acceptable weight cost, although methanol and ammonia remain somewhat high for certain vessels like Ahto 14, Ahto 15, Ahto 21, and Ahto 23. However, since shorter refueling intervals are feasible during peak periods, these fuels could still serve as viable MDO alternatives from a weight cost perspective.

Table 10. Tank volume [m^3] needs of the entire fleet using alternative fuels within an optimized range.

	Original Tank Volume	MDO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO-01	5.3	0.5	1.1	0.6	0.5	4.9	5.3	1.5	1.7
AHTO-02	5.3	1.8	4.0	2.1	1.9	18.1	19.4	5.5	6.1
AHTO-06	0.9	0.5	1.0	0.5	0.5	4.6	5.0	1.4	1.6
AHTO-07	5.3	0.4	0.8	0.4	0.4	3.6	3.8	1.1	1.2
AHTO-09	5.3	0.6	1.3	0.7	0.6	5.8	6.3	1.8	2.0
AHTO-12	2.3	0.08	0.2	0.09	0.08	0.8	0.8	0.2	0.3
AHTO-14	1.3	3.7	8.3	4.3	4.0	37.5	40.2	11.4	12.7
AHTO-15	2.5	3.0	6.8	3.5	3.2	30.6	32.8	9.3	10.4
AHTO-17	0.9	0.5	1.2	0.6	0.6	5.3	5.7	1.6	1.8
AHTO-19	0.9	0.8	1.8	0.9	0.8	7.9	8.5	2.4	2.7
AHTO-20	0.9	0.9	2.0	1.0	1.0	9.0	9.6	2.7	3.0
AHTO-21	0.9	1.4	3.1	1.6	1.5	13.9	14.9	4.2	4.7
AHTO-23	0.9	2.2	5.0	2.6	2.4	22.3	23.9	6.8	7.6
AHTO-25	4.6	4.2	9.5	4.9	4.5	42.5	45.5	12.9	14.4
AHTO-26	4.6	3.9	8.8	4.6	4.2	39.6	42.5	12.0	13.4
AHTO-27	4.6	1.7	3.8	2.0	1.8	17.1	18.3	5.2	5.8
AHTO-28	4.6	2.2	4.9	2.6	2.3	22.1	23.7	6.7	7.5
AHTO-29	3.4	1.3	2.8	1.5	1.3	12.6	13.6	3.8	4.3

Table 10 outlines the tank volume requirements for the fleet when utilizing alternative fuels within an optimized range to cover peak energy demands over a 10-day period without refueling. Similarly to MDO, some ships face volume requirements that exceed their original tank capacity, particularly for methanol, ammonia, and gaseous fuels like biomethane and hydrogen. This challenge is more pronounced for vessels with higher peak operational demands, such as Ahto 14, Ahto 15, Ahto 21, and Ahto 23. For smaller vessels like pilot boats, the increased tank volume required by these fuels may surpass onboard storage limits and impact stability. In contrast, biodiesel and HVO100 exhibit more manageable volume requirements; biodiesel requires only a slight increase in tank size, while HVO100 can reduce the necessary tank capacity, aligning well with existing vessel designs. Additionally, liquid fuels like methanol, biodiesel, HVO100, and ammonia can be stored in retrofitted original tanks, potentially lowering retrofit costs. However, gaseous fuels such as biomethane and hydrogen, stored under conditions of −15 °C and 25 MPa, incur high volume requirements. Although liquefied storage could reduce tank size, gaseous tanks are often placed on deck, which can raise the vessel's center of gravity and impact stability.

Overall, liquid fuels emerge as the most feasible for maintaining original tank designs for peak-time scenarios in many vessels. Reducing operational range post-retrofitting could further optimize tank size and weight, enhancing safety margins and space utilization. For vessels with high operational demands, alternative fuel feasibility might be improved by adjusting tank sizes to meet peak-time energy needs, with the option for shorter refueling intervals to minimize volume requirements.

5.3. Operational Cost

The fleet's annual fuel consumption using various alternative fuels relative to conventional MDO is compared in detail, highlighting each fuel's distinct characteristics (Table 11). Hydrogen stands out with significantly lower consumption compared to MDO, owing to the high efficiency of fuel cells, which convert hydrogen into energy more effectively than combustion engines. This efficiency makes hydrogen a promising option for high-demand vessels, provided its storage and safety challenges can be addressed. Similarly, biomethane benefits from efficient combustion in engines designed for gaseous fuels, resulting in reduced fuel consumption compared to MDO. However, gaseous fuels like hydrogen and biomethane require deck-mounted storage tanks, which impact space and vessel stability. Methanol and ammonia, in contrast, require a near doubling of the fuel volume of MDO to meet the same energy demands due to their lower energy density. This is especially notable for high-demand vessels like Ahto 02 and Ahto 15. While ammonia has a slightly higher energy density than methanol, both fuels demand larger tank capacities or more frequent refueling, limiting their practicality in space-constrained vessels. Among biofuels, biodiesel and HVO100 perform closest to MDO. Biodiesel shows only a slight increase in annual fuel consumption, thanks to its relatively high energy density, making it an easy substitute with minimal operational impact. HVO100 is particularly favorable, often requiring less fuel than MDO, making it well-suited for vessels with high energy demands or limited storage capacity. Both biodiesel and HVO100 provide efficient, high-density energy sources compatible with existing storage infrastructure, offering practical, low-impact alternatives to MDO.

Table 11. Yearly fuel consumption of the entire fleet with alternative fuels.

Ship	MDO	Methanol		Biodiesel		HVO	H_2 Blue	H_2 Blue	Ammonia		Biomethane	
		Main Fuel	Pilot Fuel	Main Fuel	Pilot Fuel		SOFC	PEM	Main Fuel	Pilot Fuel	Main Fuel	Pilot Fuel
AHTO-01	614	1140	60.0	688	36	595	168	173	872	218	675	21
AHTO-02	25,356	47,049	2476	28,405	1495	24,551	6917	7156	35,990	8998	27,843	861
AHTO-06	10,080	18,703	984	11,292	594	9760	2750	2845	14,307	3577	11,069	342
AHTO-07	829	1538	81	929	49	803	226	234	1177	294	910	28
AHTO-09	2897	5374	283	3245	171	2805	790	818	4111	1028	3181	98.4
AHTO-12	512	951	50	574	30	496	140	147	727	182	563	17
AHTO-14	27,531	51,084	2689	30,842	1623	26,657	7511	7770	39,077	9769	30,232	935
AHTO-15	102,786	190,720	10,038	115,144	6060	99,523	28,041	29,007	145,891	36,473	112,868	3491
AHTO-17	70,010	13,006	685	7852	413	6787	1912	1978	9949	2487	7697	238
AHTO-19	11,239	20,853	1098	12,590	663	10,882	3066	3172	15,952	3988	12,341	382
AHTO-20	14,119	26,198	1379	15,817	835	13,671	3852	3985	20,040	5010	15,504	480
AHTO-21	13,351	24,773	1304	14,956	787	12,927	3642	3768	18,950	4738	14,661	453
AHTO-23	26,322	48,841	2571	29,487	1552	25,487	7181	7428	373,614	9340	28,904	894
AHTO-25	90,590	168,090	8847	101,482	5341	87,714	24,713	25,566	128,581	32,145	99,475	3077
AHTO-26	66,038	122,534	6449	73,978	3894	63,942	18,016	18,637	937,323	23,433	72,515	2243
AHTO-27	47,408	87,967	4630	53,109	2795	45,903	12,933	13,379	67,290	16,823	52,059	1610
AHTO-28	8193	15,201	800	9178	483	79,323	2235	2312	11,628	2907	8996	278
AHTO-29	10,950	20,319	1069	12,267	646	10,603	2987	3090	15,543	3886	12,024	372

Table 12 illustrates the yearly operational costs (EUR) for the fleet across various alternative fuels and propulsion configurations, providing insight into the economic impact of each option relative to conventional MDO. Methanol shows a moderate cost increase compared to MDO across most vessels, reflecting its current higher price due to lower energy density and infrastructure requirements, though this cost may decrease as methanol production scales. Biodiesel and HVO100 show higher operational costs, with biodiesel consistently more expensive than MDO due to its production process, while HVO100, though more efficient, remains costly as a relatively new fuel. However, as demand for biodiesel and HVO100 grows, advancements in production and distribution are likely to drive costs down.

Table 12. Yearly operational cost (EUR) of the entire fleet with alternative fuels.

	MGO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO-01	413	475	800	866	838	867	661	790
AHTO-02	17,039	19,590	33,017	35,747	34,587	35,779	27,280	32,599
AHTO-06	6774	7788	13,125	14,211	13,749	14,223	10,845	12,959
AHTO-07	557	640	1079	1169	1131	1170	892	1066
AHTO-09	1946	2238	3772	4083	3951	4087	3116	3724
AHTO-12	344	396	667	722	699	723	551	659
AHTO-14	18,501	21,270	35,849	38,813	37,553	38,848	29,621	35,395
AHTO-15	69,072	79,410	133,840	144,905	140,203	145,037	110,586	132,144
AHTO-17	4710	5415	9127	9882	9561	9891	7541	9012
AHTO-19	7552	8683	14,634	15,844	15,330	15,858	12,091	14,449
AHTO-20	9488	10,908	18,385	19,905	19,259	19,923	15,191	18,152
AHTO-21	8972	10,315	17,385	18,822	18,211	18,839	14,364	17,164
AHTO-23	17,689	20,336	34,275	37,108	35,904	37,142	28,320	33,840
AHTO-25	60,876	69,987	117,959	127,711	123,567	127,828	97,464	116,464
AHTO-26	44,378	51,019	85,990	93,099	90,078	93,184	71,049	84,900
AHTO-27	31,858	36,627	61,732	66,835	64,666	66,896	51,006	60,949
AHTO-28	5505	6329	10,668	11,550	11,175	11,560	8814	10,533
AHTO-29	7359	8460	14,259	15,438	14,937	15,452	11,781	14,078

Hydrogen, used with both SOFC and PEM fuel cells, demonstrates considerably higher costs compared to MDO. While hydrogen fuel cells are efficient, the high current costs stem from limited infrastructure, production complexities, and storage requirements. As hydrogen technology matures and renewable hydrogen production expands, costs are expected to decrease, potentially making it a more competitive option for sustainable maritime energy. Ammonia and biomethane similarly show increased operational costs compared to MDO, with ammonia's infrastructure needs contributing to its higher cost, although like other fuels, its price could drop with further investment and advancements in production and storage technology.

While most alternative fuels currently show higher operational costs than MDO, the price landscape for these fuels is likely to evolve as production technologies improve and adoption rates increase. As economies of scale and supply chains develop for sustainable fuels, operational costs for options like methanol, hydrogen, and biodiesel are expected to decrease, making these fuels more viable in the long term.

5.4. Alternative Fuels' GHG Emissions

This study explored potential fuel alternatives for the Estonian State Fleet's pilot boats. E-fuels, which are synthetic fuels produced from captured CO_2 and hydrogen, showed the best results in terms of total GHG emissions. Despite their promise for the future, their current availability and readiness for use remain limited [128]. GHG emissions for the selected fuel alternatives were calculated based on estimated fuel consumption (Figure 5). Among conventional fuels, biomethane stands out as the most promising alternative, achieving a 59.0% reduction in emissions compared to MDO. HVO follows with a 43.6% reduction, and biodiesel ranks third with a 41.2% reduction in emissions relative to MDO.

Focusing on fuels' life cycle emissions, the results of this study align with findings from other sources [129,130], showing that the WtW GHG emissions of ammonia and hydrogen can exceed those of marine diesel oil. This is primarily due to their high WtT emissions, as illustrated in Figure 6. However, it is important to note that hydrogen and ammonia could significantly reduce WtW GHG emissions if produced using green renewable electricity or through steam reforming of natural gas combined with carbon capture technology [131]. Similarly, carbon-neutral biofuels emerge as promising alternatives for reducing GHG emissions, as their lower WtT emissions contribute to reduced total WtW emissions.

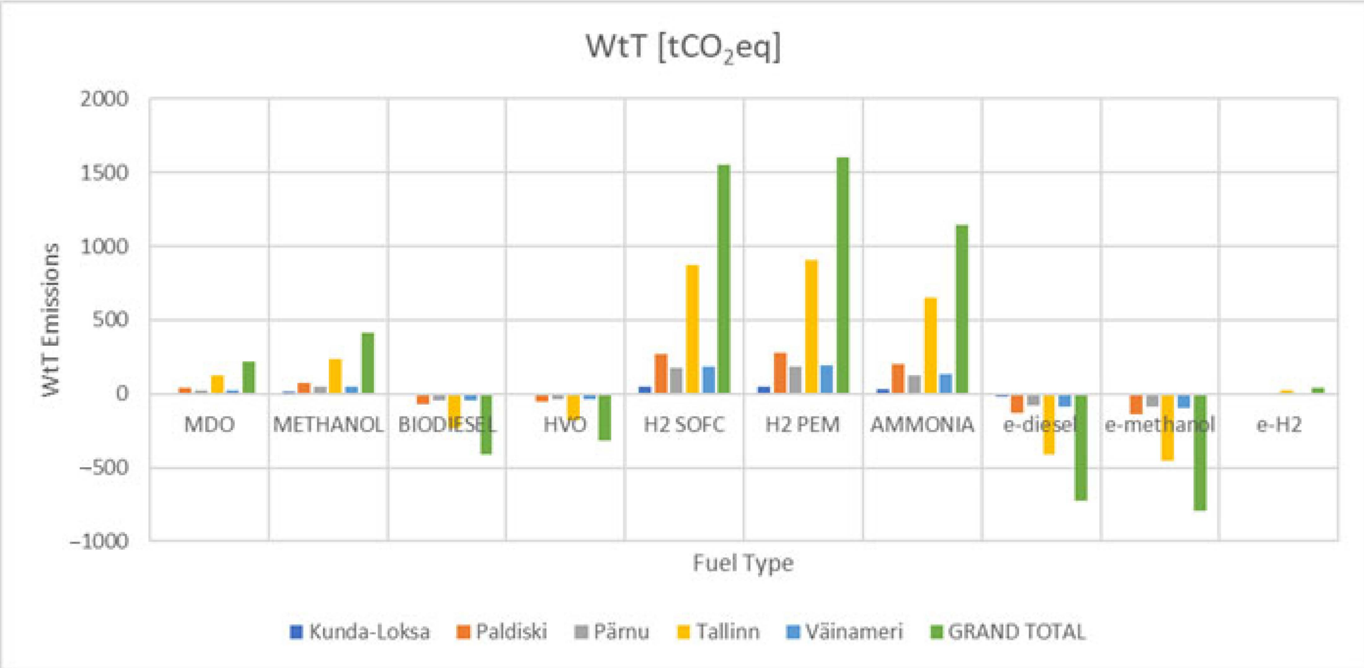

Figure 6. WtT emissions of alternative fuels.

E-fuels are widely regarded as promising energy carriers for the maritime industry and other transportation sectors, such as aviation [132,133]. Derived primarily from green hydrogen, their production requires vast amounts of renewable energy. A study by Transport and Environment highlights the significant focus on e-fuel projects but warns that production volumes will fall short of future demand, particularly as larger quantities of green fuels will be needed to meet FuelEU targets [134]. The study also identifies Denmark and Spain as leading producers and users of e-fuels, while Estonia is excluded due to limited availability, demand, and active projects. Additionally, the high cost of e-fuels [135] further complicates their adoption, making them an impractical option for the Baltic region at present. Given these challenges, carbon-neutral biofuels emerge as the most viable alternatives. The analysis focuses on these biofuels, as they offer a feasible solution within the region of operation, unlike e-fuels, which remain unfeasible for the time being.

The production of sustainable biofuels depends on a sustainable biomass feedstock. However, accurately estimating the availability of these feedstocks is challenging. While several sources offer estimates, there is a lack of comprehensive data on current production and land productivity [136]. As a result, forecasts are often unclear, and different approaches to estimating future biomass production and availability might lead to inconsistent and unreliable figures. Nevertheless, while the current use of biofuels in marine engine applications is very limited, there is significant potential for biofuels to capture a larger share of the total maritime fuel consumption and support the EU and IMO's GHG-reduction ambitions for the maritime industry. Recent regulatory developments in the EU covering GHG emissions and the lifecycle aspect of fuels provide several measures in line with the climate goals that could accelerate their adoption [137]. Carbon-neutral fuels, such as the biofuels identified in this study as the second most promising group, are characterized by combustion that contributes little to no net GHG emissions to the atmosphere. Assessing biofuels as renewable energy sources requires accounting for their overall environmental impact, production, distribution and supply chains, and storage in a lifecycle analysis methodology.

The shipping industry operates in a volatile market, carrying significant managerial risks. In the context of biofuels, rapid price fluctuations can make it challenging for companies to predict costs and plan effectively for the future. This uncertainty poses additional risks for stakeholders, particularly those heavily dependent on a consistent supply of specific fuels. From a managerial perspective, it is increasingly important not only to assess finances and market fluctuations but also to evaluate the feasibility and availability of new technologies and fuels. Pilot boats typically have a lifespan of 20–30 years. Given the moderate pace of regulatory changes aimed at achieving a carbon-free future, it may not be practical for smaller sectors of the shipping industry, such as pilotage, to pursue drastic shifts prematurely. Instead, the focus in selecting alternative fuels might need to prioritize local availability over GHG emissions, addressing the unique challenges posed by market volatility and operational constraints.

5.4.1. Biomethane

The study results indicate that biomethane is a highly promising fuel alternative for reducing the fleet's GHG emissions. Calculations show that switching to biomethane could reduce the pilot fleet's total WtW emissions by 59%. Beyond its emissions-reduction potential, biomethane is also an attractive option due to its strong availability in Estonia.

The evolution and feasibility of biogas across the world is currently uneven. The development depends on the availability of feedstocks, but also on the policies that encourage its production and use. Europe is the largest producer of biogas today [138]. According to the European Commission, Estonia can replace about 25% of the current natural gas consumption (imports) with biomethane [139]. Currently, 20% of its sustainable biomethane potential is deployed.

The production of biomethane in Estonia is rising [140]. The biomethane production in Estonia has grown from 0 GWh by the end of 2017 to 210 GWh by the end of 2023. There are around eight upcoming biogas plant projects under development, which can continue the growth to nearly 700 GWh [94]. At the moment, most of the produced biomethane is used in the transport sector, and there are several filling stations around the country [95]. In order to increase the consumption of biofuels in Estonia, the Estonian government plans to develop biomethane production based on local feedstock [141]. The target is to produce 100 million m^3 of biomethane by 2035, equivalent to 1 terawatt-hour per year.

Biomethane has been included in this study not only for its environmental benefits but also because it aligns with Estonia's strategic targets for promoting renewable energy sources. The Estonian government has identified the widespread use of biomethane as a key objective to support the country's transition to cleaner energy systems. However, its practical application areas, especially in the maritime industry, remain a topic of ongoing discussion. While the results of this study highlight the significant potential of biomethane to reduce GHG emissions, they also underscore its current limitations for use in pilot vessels. Biomethane's volume cost is substantially higher compared to other alternatives, which poses challenges for vessels with limited storage capacities. Additionally, the operational safety of biomethane, particularly concerning methane leakage and high-pressure storage requirements, is another critical issue that must be addressed before its adoption in maritime applications can become widespread. These limitations suggest that biomethane cannot yet be considered the best alternative for pilot vessels unless advancements are made in storage technologies and safety measures. However, given Estonia's strategic commitment to biomethane and the potential for future technological improvements, its inclusion in this study provides valuable insights for policymakers and industry stakeholders aiming to evaluate its feasibility under varying conditions.

5.4.2. HVO

According to the current study, using hydrotreated vegetable oil would reduce the pilot fleet's emissions by 43.6% in comparison with conventional marine diesel oil. HVO is gaining recognition as a leading fuel for meeting future energy needs. Made from sustainable sources like vegetable oils, vegetable, or residual raw materials, and even used cooking fats and oils, this innovative alternative is also considered as one of the key solutions for the future of the maritime industry.

One of the big benefits of using HVO is its bunkering. HVO can be bunkered similarly to MGO, but it is essential to take precautions to prevent contamination with other fuels. Also, some adjustments to the bunkering process may be required to accommodate HVO's unique characteristics, such as its lower density. It must be kept in mind that HVO is less corrosive and produces cleaner emissions than MGO, which could result in reduced maintenance requirements and extended periods between engine overhauls. While the long-term effects on engine wear are still under investigation, HVO is generally known to enhance fuel lubricity, which may benefit engine longevity [142].

The biggest challenges of using HVO are connected to the availability and price. HVO is not as widely accessible as conventional marine diesel, but its availability is expanding, particularly in areas prioritizing carbon emission reductions. It is more readily available in Europe and North America, where there is a stronger focus on sustainable fuel alternatives. HVO is also more costly due to the complexities of its production and the expense of its raw materials. However, its higher price may, in the future, be partially supported by governmental subsidies or incentives aimed at promoting the use of renewable fuels.

According to the Ministry of Climate of Estonia, increasing the adoption of HVO is one of the opportunities with the greatest potential for reducing greenhouse gas emissions [143]. In reality, the availability of HVO for shipping purposes is in the very early stages of development. Therefore, the transition to HVO in the pilot fleet would require additional input financially as well as solving challenges with the actual bunkering possibilities. Nevertheless, there are clear offers, for example, for trials using HVO and pilot boats [144]. Therefore, this alternative should be kept in focus for the future as the market expands and more solutions arise for smaller areas and more narrow markets.

5.4.3. Biodiesel

Biodiesel ranked as the third-lowest emitting fuel alternative on a WtW basis for the Estonian pilot fleet. Its greatest advantage lies in its compatibility with existing infrastructure, as no modifications to machinery systems or fuel tanks are required to transition to biodiesel.

According to the industry [145,146], there are several aspects of whether the supply can meet the demand for biodiesel. In addition, there are concerns over the quality of used cooking oil (which is the primary feedstock for biodiesel). Estimates of future biodiesel prices vary significantly, with projections for 2050 ranging from 25% to 300% higher than the cost of fossil fuels [147].

Apart from the above-mentioned, there are also practical challenges associated with using biodiesel in higher concentrations, which could lead to additional operational costs that are not reflected in current price estimates. Issues related to engine compatibility, fuel quality and stability, and potentially higher insurance would raise the total OPEX.

These uncertainties are further additional risks to meeting sustainability goals and GHG reduction targets, even though, at this point, biodiesel is a fruitful alternative today. Nevertheless, while focusing on hands-on actions that can be executed from this day and available infrastructure, biodiesel would potentially be the solution to reduce GHG emissions temporarily. In the long term, this transition might not be the most lucrative.

6. Conclusions

This study assessed the GHG emissions of the Estonian pilot fleet using various alternative fuels suitable for this sector. Fully electric and hybrid propulsion systems were excluded due to inconsistent electricity generation methods, variations in GHG guidelines, insufficient infrastructure, and limited applicability for pilotage operations. Using 2023 fuel consumption data, emissions were calculated and projected for alternative fuels based on a lifecycle well-to-wheel (WtW) approach. Several assumptions were necessary, which represent the study's primary limitations.

One limitation of this study is that the fuel cost data reflects current market prices at the time of analysis. Market conditions, geopolitical factors, technological advancements, and regulatory changes will significantly impact fuel prices over time. As such, the findings of this study are tied to present price levels and do not represent future economic scenarios, particularly for emerging alternative fuels where price volatility is expected to be higher.

Fuel costs were based on global market data, focusing on prices in Estonia and nearby countries. Availability was estimated using existing infrastructure and projected developments. Engine performance and efficiency were derived from technical specifications, including brake-specific fuel consumption (BSFC) values calculated using standardized methods. Partial load BSFC values were estimated using linear regression due to incomplete data for some engines.

The results identified biomethane as the most promising alternative, reducing WtW emissions by 59% compared to marine diesel oil (MDO). Biomethane also offers advantages such as local availability, economic feasibility, and competitive pricing. HVO100 and biodiesel showed reductions of 43.6% and 41.2%, respectively, and are compatible with existing infrastructure, minimizing transition costs. E-fuels, including e-diesel, e-methanol, and e-hydrogen, demonstrated strong GHG reduction potential when produced with renewable energy. However, high production costs, low availability, and storage challenges limit their current feasibility, especially in Estonia. Gaseous fuels like hydrogen pose additional safety and design challenges.

This study emphasizes the importance of lifecycle emissions analysis for alternative fuels, whose adoption relies on infrastructure, market conditions, and regulatory support, with further research needed on pilot station capabilities and economic viability. Future studies should focus on methodologies to evaluate GHG emissions for fully electric and hybrid ships, considering broader operational and environmental factors. Long-term assessments should address the economic and logistical implications of transitioning to alternative fuels, ensuring a comprehensive approach to decarbonizing the Estonian pilot fleet.

Author Contributions: Conceptualization, R.O. and Y.G.; methodology, R.O., Y.G. and A.L.; validation, R.O., Y.G. and A.L.; formal analysis, R.O. and Y.G.; investigation, A.L. and R.O.; data curation, R.O. and Y.G.; writing—original draft preparation, R.O. and Y.G.; writing—review and editing, R.O., A.L., U.T. and J.K.; visualization, R.O. and Y.G.; supervision, U.T. and J.K.; project administration, R.O.; funding acquisition, R.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from Horizon-Widera-2023-Access-02-02 under the grant agreement no. 101159424 project titled "Twinning to enable Baltic Sea vessels to meet Fit-for-55 regulations" by the European Research Executive Agency (REA) delegated by the European Commission. The views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or REA. Neither the European Union nor the granting authority can be held responsible for these views and opinions.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. European Commission. The European Green Deal. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 23 December 2024).
2. European Environment Agency. EU Maritime Transport: First Environmental Impact Report Acknowledges Good Progress Towards Sustainability and Confirms That More Effort Is Needed to Prepare for Rising Demand. Available online: https://www.eea.europa.eu/highlights/eu-maritime-transport-first-environmental (accessed on 23 December 2024).
3. Armstrong, J. *Climate Impacts of Exemptions to EU's Shipping Proposals Arbitrary Exemptions Undermine Integrity of Shipping Laws Transport & Environment Further Information Acknowledgements*; Transport & Environment: Brussels, Belgium, 2022.
4. Pilotage. Available online: https://www.imo.org/en/ourwork/safety/pages/pilotage.aspx (accessed on 23 December 2024).
5. Lappalainen, J.; Kunnaala, V.; Tapaninen, U. Present Pilotage Practices in Finland. *WMU J. Marit. Aff.* **2014**, *13*, 77–99. [CrossRef]
6. Kunnaala, V.; Lappalainen, J.; Tapaninen, U. Review of Pilotage Processes and Indicators in Pilotage Organisations. *WMU J. Marit. Aff.* **2013**, *12*, 99–114. [CrossRef]
7. Marine-Pilots.Com. What Is a Pilot Boat? Available online: https://www.marine-pilots.com/articles/733662-what-is-pilot-boat (accessed on 23 December 2024).
8. EUR-Lex. Directive—2010/65—EN. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32010L0065 (accessed on 23 December 2024).
9. EU Union Submission to the 77 Th Session of the International Maritime Organization's Marine Environment Protection Committee Proposing to Introduce Life Cycle Guidelines to Estimate Well-to-Wake Greenhouse Gas (GHG) Emissions of Sustainable Alternative Fuels to Incentivise Their Uptake at Global Level. 2021. Available online: https://data.consilium.europa.eu/doc/document/ST-10585-2021-INIT/en/pdf (accessed on 1 January 2025).
10. Waterborne.Eu. Zero Emission Waterborne Transport. Available online: https://www.waterborne.eu/partnership/partnership (accessed on 23 December 2024).
11. Finnpilot Continues Partnership with SeaFocus. Available online: https://seafocus.international/news-and-blogs/f/finnpilot-continues-partnership-with-seafocus (accessed on 23 December 2024).
12. DanPilot. *Environmental Social Governance, DanPilot Creating Safety at Sea and in Port*; DanPilot: Svendborg, Denmark, 2023.
13. NetZeroCities. Gothenburg's Pilot Activity: FastForward Green City Zone. Available online: https://netzerocities.eu/gothenburgs-pilot-activity-fastforward-green-city-zone/ (accessed on 23 December 2024).
14. Johansson, M.; Vierth, I.; Holmgren, K.; Cullinane, K. The Climate and Environmental Effects of Policies for Moving Freight Transport from Road to Other Modes: The Case of Sweden. *Case Stud. Transp. Policy* **2024**, *15*, 101151. [CrossRef]
15. Ministry of Climate and Environment. Introducing Zero-Emission Requirements in the World Heritage Fjords. 2024. Available online: https://www.regjeringen.no/en/aktuelt/introducing-zero-emission-requirements-in-the-world-heritage-fjords/id3051481/#:~:text=The%20government%20is%20introducing%20zero,fjords%20and%20promote%20sustainable%20tourism (accessed on 2 January 2025).
16. EUR-Lex. Regulation—2023/1805—EN. Available online: https://eur-lex.europa.eu/eli/reg/2023/1805/oj (accessed on 23 December 2024).
17. European Commission. Reducing Emissions from the Shipping Sector. Available online: https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en (accessed on 23 December 2024).

18. European Commission. EU Emissions Trading System (EU ETS). Available online: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (accessed on 23 December 2024).
19. Zamboni, G.; Scamardella, F.; Gualeni, P.; Canepa, E. Comparative Analysis among Different Alternative Fuels for Ship Propulsion in a Well-to-Wake Perspective. *Heliyon* **2024**, *10*, e26016. [CrossRef] [PubMed]
20. Paulauskiene, T.; Bucas, M.; Laukinaite, A. Alternative Fuels for Marine Applications: Biomethanol-Biodiesel-Diesel Blends. *Fuel* **2019**, *248*, 161–167. [CrossRef]
21. Mohd Noor, C.W.; Noor, M.M.; Mamat, R. Biodiesel as Alternative Fuel for Marine Diesel Engine Applications: A Review. *Renew. Sustain. Energy Rev.* **2018**, *94*, 127–142. [CrossRef]
22. Jeevahan, J.; Mageshwaran, G.; Joseph, G.B.; Raj, R.B.D.; Kannan, R.T. Various Strategies for Reducing Nox Emissions of Biodiesel Fuel Used in Conventional Diesel Engines: A Review. *Chem. Eng. Commun.* **2017**, *204*, 1202–1223. [CrossRef]
23. Mirhashemi, F.S.; Sadrnia, H. NOX Emissions of Compression Ignition Engines Fueled with Various Biodiesel Blends: A Review. *J. Energy Inst.* **2020**, *93*, 129–151. [CrossRef]
24. Saxena, V.; Kumar, N.; Saxena, V.K. A Comprehensive Review on Combustion and Stability Aspects of Metal Nanoparticles and Its Additive Effect on Diesel and Biodiesel Fuelled C.I. Engine. *Renew. Sustain. Energy Rev.* **2017**, *70*, 563–588. [CrossRef]
25. Demirbaş, A. Biodiesel Production from Vegetable Oils by Supercritical Methanol. *J. Sci. Ind. Res.* **2005**, *64*, 858–865. Available online: https://www.researchgate.net/publication/228658417_Biodiesel_production_from_vegetable_oils_by_supercritical_methanol (accessed on 23 December 2024).
26. Kesieme, U.; Pazouki, K.; Murphy, A.; Chrysanthou, A. Biofuel as an Alternative Shipping Fuel: Technological, Environmental and Economic Assessment. *Sustain. Energy Fuels* **2019**, *3*, 899–909. [CrossRef]
27. Araujo, V.K.W.S.; Hamacher, S.; Scavarda, L.F. Economic Assessment of Biodiesel Production from Waste Frying Oils. *Bioresour. Technol.* **2010**, *101*, 4415–4422. [CrossRef] [PubMed]
28. You, Y.; Der Shie, J.L.; Chang, C.Y.; Huang, S.H.; Pai, C.Y.; Yu, Y.H.; Chang, C.H. Economic Cost Analysis of Biodiesel Production: Case in Soybean Oil. *Energy Fuels* **2007**, *22*, 182–189. [CrossRef]
29. Nasir, H.; Tian, T. A Comparative Study on Alternative Marine Fuels: Economic, Technology, Environmental and Safety Issues. Master's Thesis, Chalmers University of Technology, Göteborg, Sweden, 2024.
30. Report—Utrecht University & Port of Amsterdam—Thesis: Assessment and Comparison of Alternative Maritime Fuels (2021). 2021. Available online: https://www.hernieuwbarebrandstoffen.nl/post/utrecht-university-port-of-amsterdam-thesis-assessment-and-comparison-of-alternative-maritime-fuels (accessed on 23 December 2024).
31. Xing, H.; Stuart, C.; Spence, S.; Chen, H. Alternative Fuel Options for Low Carbon Maritime Transportation: Pathways to 2050. *J. Clean. Prod.* **2021**, *297*, 126651. [CrossRef]
32. Livaniou, S.; Papadopoulos, G.A. Liquefied Natural Gas (LNG) as a Transitional Choice Replacing Marine Conventional Fuels (Heavy Fuel Oil/Marine Diesel Oil), towards the Era of Decarbonisation. *Sustainability* **2022**, *14*, 16364. [CrossRef]
33. Lee, H.; Lee, J.; Roh, G.; Lee, S.; Choung, C.; Kang, H. Comparative Life Cycle Assessments and Economic Analyses of Alternative Marine Fuels: Insights for Practical Strategies. *Sustainability* **2024**, *16*, 2114. [CrossRef]
34. Wang, Y.; Wright, L.A.; Bergman, M. A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation. *World* **2021**, *2*, 456–481. [CrossRef]
35. Ampah, J.D.; Yusuf, A.A.; Afrane, S.; Jin, C.; Liu, H. Reviewing Two Decades of Cleaner Alternative Marine Fuels: Towards IMO's Decarbonization of the Maritime Transport Sector. *J. Clean. Prod.* **2021**, *320*, 128871. [CrossRef]
36. Bilgili, L. A Systematic Review on the Acceptance of Alternative Marine Fuels. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113367. [CrossRef]
37. Karvounis, P.; Tsoumpris, C.; Boulougouris, E.; Theotokatos, G. Recent Advances in Sustainable and Safe Marine Engine Operation with Alternative Fuels. *Front. Mech. Eng.* **2022**, *8*, 994942. [CrossRef]
38. Rivarolo, M.; Rattazzi, D.; Magistri, L.; Massardo, A.F. Multi-Criteria Comparison of Power Generation and Fuel Storage Solutions for Maritime Application. *Energy Convers. Manag.* **2021**, *244*, 114506. [CrossRef]
39. Van Veldhuizen, B.; van Biert, L.; Visser, K.; Hopman, H. Comparative Analysis of Alternative Fuels for Marine SOFC Systems. In Proceedings of the 15th International Symposium on Practical Design of Ships and Other Floating Structures—PRADS 2022, Dubrovnik, Croatia, 9–13 October 2022; Available online: https://www.researchgate.net/publication/366971670_Comparative_Analysis_of_Alternative_Fuels_for_Marine_SOFC_Systems (accessed on 23 December 2024).
40. Interview with Bengt Ramne. Available online: https://www.fastwater.eu/news/wp-news/interview-with-bengt-ramne (accessed on 23 December 2024).
41. Offshore Energy. World's 1st Methanol-Powered Pilot Boat Launched. Available online: https://www.offshore-energy.biz/worlds-1st-methanol-powered-pilot-boat-launched/ (accessed on 23 December 2024).
42. Hansson, J.; Månsson, S.; Brynolf, S.; Grahn, M. Alternative Marine Fuels: Prospects Based on Multi-Criteria Decision Analysis Involving Swedish Stakeholders. *Biomass Bioenergy* **2019**, *126*, 159–173. [CrossRef]

43. Foretich, A.; Zaimes, G.G.; Hawkins, T.R.; Newes, E. Challenges and Opportunities for Alternative Fuels in the Maritime Sector. *Marit. Transp. Res.* **2021**, *2*, 100033. [CrossRef]
44. Welaya, Y.M.A.; El Gohary, M.M.; Ammar, N.R. A Comparison between Fuel Cells and Other Alternatives for Marine Electric Power Generation. *Int. J. Nav. Archit. Ocean. Eng.* **2011**, *3*, 141–149. [CrossRef]
45. Moirangthem, K. *Alternative Fuels for Marine and Inland Waterways*; European Commission—Joint Research Centre Technical Reports; Institute for Energy and Transport: Petten, The Netherlands, 2016. [CrossRef]
46. Helgason, R.; Cook, D.; Davíðsdóttir, B. An Evaluation of the Cost-Competitiveness of Maritime Fuels—A Comparison of Heavy Fuel Oil and Methanol (Renewable and Natural Gas) in Iceland. *Sustain. Prod. Consum.* **2020**, *23*, 236–248. [CrossRef]
47. Dublin Port. Dublin Port Company Completes Successful First Round of HVO Fuel Trial in Pilot Boat. Available online: https://www.dublinport.ie/fuel-trial-in-pilot-boat/ (accessed on 23 December 2024).
48. Alkaner, S.; Zhou, P. A Comparative Study on Life Cycle Analysis of Molten Carbon Fuel Cells and Diesel Engines for Marine Application. *J. Power Sources* **2006**, *158*, 188–199. [CrossRef]
49. Deniz, C.; Zincir, B. Environmental and Economical Assessment of Alternative Marine Fuels. *J. Clean Prod.* **2016**, *113*, 438–449. [CrossRef]
50. Law, L.C.; Foscoli, B.; Mastorakos, E.; Evans, S. A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost. *Energies* **2021**, *14*, 8502. [CrossRef]
51. Crepeau, G.; Gaillard, P.; Van Der Merwe, D.; Schaberg, P. Engine Impacts and Opportunities of Various Fuels, Including GTL and FAME: Toward Specific Engine Calibration? *SAE Tech. Pap.* **2009**. [CrossRef]
52. Perčić, M.; Vladimir, N.; Koričan, M.; Jovanović, I.; Haramina, T. Alternative Fuels for the Marine Sector and Their Applicability for Purse Seiners in a Life-Cycle Framework. *Appl. Sci.* **2023**, *13*, 13068. [CrossRef]
53. Sjölin, K.; Holmgren, E. A Proton Exchange Membrane & Solid Oxide Fuel Cell Comparison. Bachelor Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2019.
54. Department of Energy. Comparison of Fuel Cell Technologies. Available online: https://www.energy.gov/eere/fuelcells/comparison-fuel-cell-technologies (accessed on 23 December 2024).
55. Pilot Boat. "World First" as Vestas Pins Hopes on Green Hydrogen to Slash Emissions by a Third. Recharge. Available online: https://www.rechargenews.com/energy-transition/pilot-boat-world-first-as-vestas-pins-hopes-on-green-hydrogen-to-slash-emissions-by-a-third/2-1-1252941?zephr_sso_ott=uXjyTa (accessed on 23 December 2024).
56. Ashrafi, M.; Lister, J.; Gillen, D. Toward a Harmonization of Sustainability Criteria for Alternative Marine Fuels. *Marit. Transp. Res.* **2022**, *3*, 100052. [CrossRef]
57. Solakivi, T.; Paimander, A.; Ojala, L. Cost Competitiveness of Alternative Maritime Fuels in the New Regulatory Framework. *Transp. Res. D Transp. Environ.* **2022**, *113*, 103500. [CrossRef]
58. Zhang, J.; Zhang, Z.; Liu, D.; Zhang, J.; Zhang, Z.; Liu, D. Comparative Study of Different Alternative Fuel Options for Shipowners Based on Carbon Intensity Index Model Under the Background of Green Shipping Development. *J. Mar. Sci. Eng.* **2024**, *12*, 2044. [CrossRef]
59. Zou, J.; Yang, B. Evaluation of Alternative Marine Fuels from Dual Perspectives Considering Multiple Vessel Sizes. *Transp. Res. D Transp. Environ.* **2023**, *115*, 103583. [CrossRef]
60. Kim, J.S.; Choi, J.H. Feasibility Study on Bio-Heavy Fuel as an Alternative for Marine Fuel. *Renew. Energy* **2023**, *219*, 119543. [CrossRef]
61. Scania Group. Scania Group Marine Power Solutions. Available online: https://www.scania.com/content/dam/scanianoe/market/master/products-and-services/engines/pdf/specs/marine/DI16094M_445-468kW.pdf.l (accessed on 23 December 2024).
62. MTU Solutions. MTU, 8V/10V 2000 M70 Marine Engine Specifications. Available online: https://www.mtu-solutions.com/eu/en.html (accessed on 23 December 2024).
63. Volvo Penta D13-MH Marine Engine Specifications. Available online: https://www.volvopenta.com/marine/all-marine-engines/d13-mh/ (accessed on 23 December 2024).
64. Volvo Penta D16-MH Marine Engine Specifications. Available online: https://pubs.volvopenta.com/ProdDocs/Home/Disclaimer?publication=47706705&lang=en-US (accessed on 23 December 2024).
65. Volvo Penta D11-MH Marine Engine Specifications. Available online: https://www.volvopenta.com/marine/all-marine-engines/d11/ (accessed on 23 December 2024).
66. Maesco FPT N40 ENT M25 Marine Engine Specifications. Available online: https://www.fptindustrial.com/en/engines/Marine/Commercial/N40 (accessed on 23 December 2024).
67. Psaraftis, H.N.; Lagouvardou, S. Ship Speed vs. Power or Fuel Consumption: Are Laws of Physics Still Valid? Regression Analysis Pitfalls and Misguided Policy Implications. *Clean. Logist. Supply Chain.* **2023**, *7*, 100111. [CrossRef]
68. Vlaskos, I.; Codan, E.; Alexandrakis, N.; Papalambrou, G.; Ioannou, M.; Kyrtatos, N.; Boom, R. Design and Performance of a Controlled Turbocharging System on Marine Diesel Engines. In Proceedings of the ASME 2006 Internal Combustion Engine Division Fall Technical Conference, ICEF 2006, Sacramento, CA, USA, 5–8 November 2006; pp. 369–379. [CrossRef]

69. Gülmez, Y. The Role of Advancing Fuel Injection Timing in Mitigating the Negative Impact of Exhaust Back-Pressure on Diesel Engines' Performance. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2023**, *238*, 280–291. [CrossRef]
70. Tauzia, X.; Hetet, J.F.; Chesse, P.; Grosshans, G.; Mouillard, L. Computer Aided Study of the Transient Performances of a Highly Rated Sequentially Turbocharged Marine Diesel Engine. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **1998**, *212*, 185–196. [CrossRef]
71. Wissner, N.; Healy, S.; Cames, M.; Sutter, J. Methanol as a Marine Fuel. Available online: https://www.oeko.de/en/publications/methanol-as-a-marine-fuel/ (accessed on 3 January 2025).
72. Man Energy Solutions. *The Methanol-Fuelled MAN B&W LGIM Engine Application*; MAN Energy Solutions: Copenhagen, Denmark, 2021.
73. Current Prices for Methanol in the 1st Quarter of 2024. Available online: https://www.penpet.com/news/methanol-1st-quarter-2024 (accessed on 3 January 2025).
74. Engines. WinGD. Available online: https://wingd.com/products-solutions/engines (accessed on 3 January 2025).
75. Dierickx, J.; Dejaegere, Q.; Peeters, J.; Sileghem, L.; Verhelst, S. Performance and Emissions of a High-Speed Marine Dual-Fuel Engine Operating with Methanol-Water Blends as a Fuel. *Fuel* **2023**, *333*, 126349. [CrossRef]
76. Estonian Ministry of Economic Affairs and Communications. *Estonian Hydrogen Roadmap 2023*; Estonian Ministry of Economic Affairs and Communications: Tallinn, Estonia, 2023.
77. Blue Hydrogen Price Index. Businessanalytiq. Available online: https://businessanalytiq.com/procurementanalytics/index/blue-hydrogen-price-index/ (accessed on 3 January 2025).
78. Methanol Institute. Methanol Price. Available online: https://www.methanol.org/methanol-price-supply-demand/ (accessed on 3 January 2025).
79. Svanberg, M.; Ellis, J.; Lundgren, J.; Landälv, I. Renewable methanol as a fuel for the shipping industry. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1217–1228. [CrossRef]
80. Szeto, W.; Leung, D.Y.C. Is Hydrotreated Vegetable Oil a Superior Substitute for Fossil Diesel? A Comprehensive Review on Physicochemical Properties, Engine Performance and Emissions. *Fuel* **2022**, *327*, 125065. [CrossRef]
81. Bayraktar, M.; Yuksel, O.; Pamik, M. An evaluation of methanol engine utilization regarding economic and upcoming regulatory requirements for a container ship. *Sustain. Prod. Consum.* **2023**, *39*, 345–356. [CrossRef]
82. Lövdahl, J.; Magnusson, M. Evaluation of Ammonia as a Potential Marine Fuel. Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2019.
83. Machaj, K.; Kupecki, J.; Malecha, Z.; Morawski, A.W.; Skrzypkiewicz, M.; Stanclik, M.; Chorowski, M. Ammonia as a Potential Marine Fuel: A Review. *Energy Strategy Rev.* **2022**, *44*, 100926. [CrossRef]
84. Zincir, B. A Short Review of Ammonia as an Alternative Marine Fuel for Decarbonised Maritime Transportation. Available online: https://drive.google.com/file/d/1L33CmDDbmMj7oh7098u1dKxOWkkCxvw4/view (accessed on 3 January 2025).
85. Sendzikiene, E.; Rimkus, A.; Melaika, M.; Makareviciene, V.; Pukalskas, S. Impact of Biomethane Gas on Energy and Emission Characteristics of a Spark Ignition Engine Fuelled with a Stoichiometric Mixture at Various Ignition Advance Angles. *Fuel* **2015**, *162*, 194–201. [CrossRef]
86. Kim, D.; Kim, S.; Oh, S.; No, S.Y. Engine Performance and Emission Characteristics of Hydrotreated Vegetable Oil in Light Duty Diesel Engines. *Fuel* **2014**, *125*, 36–43. [CrossRef]
87. Zhou, X.; Li, T.; Wang, N.; Wang, X.; Chen, R.; Li, S. Pilot Diesel-Ignited Ammonia Dual Fuel Low-Speed Marine Engines: A Comparative Analysis of Ammonia Premixed and High-Pressure Spray Combustion Modes with CFD Simulation. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113108. [CrossRef]
88. Niki, Y.; Nitta, Y.; Sekiguchi, H.; Hirata, K. Diesel Fuel Multiple Injection Effects on Emission Characteristics of Diesel Engine Mixed Ammonia Gas into Intake Air. *J. Eng. Gas Turbine Power* **2019**, *141*, 061020. [CrossRef]
89. Gross, C.W.; Kong, S.C. Performance Characteristics of a Compression-Ignition Engine Using Direct-Injection Ammonia—DME Mixtures. *Fuel* **2013**, *103*, 1069–1079. [CrossRef]
90. Bloom Energy. *Hydrogen Power Generation and the Significance of Efficiency 2*; Bloom Energy: San Jose, CA, USA, 2023.
91. McPhail, S.; Leto, L.; Boigues-Muñoz, C. *The Yellow Pages of SOFC Technology—International Status of SOFC Deployment 2012–2013*; Enea: Rome, Italy, 2013.
92. Cummins Inc. *Stationary Solutions Fuel Cell Power Systems*; Cummins Inc.: Columbus, IN, USA, 2024.
93. Quantum Commodity Intelligence. News, Prices, Analysis & Data. Available online: https://www.qcintel.com/ (accessed on 3 January 2025).
94. Estonian Biogas Association Biogaas & Biometaan. Eesti Biogaasi Assotsiatsioon. Available online: https://www.eestibiogaas.ee/biogaas-biometaan (accessed on 2 January 2025).
95. Thori Tanklad. Eesti. Available online: https://www.thoritanklad.ee/ (accessed on 2 January 2025).
96. Sugiyama, K.; Goto, I.; Kitano, K.; Mogi, K.; Honkanen, M. Effects of Hydrotreated Vegetable Oil (HVO) as Renewable Diesel Fuel on Combustion and Exhaust Emissions in Diesel Engine. *SAE Int. J. Fuels Lubr.* **2011**, *5*, 205–217. [CrossRef]

97. Hulkkonen, T.; Hillamo, H.; Sarjovaara, T.; Larmi, M. Experimental Study of Spray Characteristics between Hydrotreated Vegetable Oil (HVO) and Crude Oil Based EN 590 Diesel Fuel. *SAE Tech. Pap.* **2011**. [CrossRef]
98. De Graaf, K.T.; Hus, I.H.E.; Van Leeuwen, H.J.; Van de Kaa, G. Towards sustainable energy technologies in the maritime industry: The dominance battle for hydrogen fuel cell technology. *Int. J. Hydrogen Energy* **2025**, *100*, 156–162. [CrossRef]
99. Wärtsilä 25 Ammonia. Available online: https://www.wartsila.com/marine/wartsila-25-ammonia (accessed on 3 January 2025).
100. Rauch, J.; Haloua, F. Calorific Value of Biomethane: Comparative Measurements Using Reference Gas Calorimeters. *J. Phys. Conf. Ser.* **2018**, *1065*, 202007. [CrossRef]
101. Ammenberg, J.; Gustafsson, M.; Eklund, M. Perspectives on Biomethane as a Transport Fuel within a Circular Economy, Energy, and Environmental System. Available online: https://www.ieabioenergy.com/blog/publications/perspectives-on-biomethane-as-transport-fuel-within-a-circular-economy-energy-and-environmental-system/ (accessed on 3 January 2025).
102. MAN B&W. ME-GI. Available online: https://www.man-es.com/marine/products/two-stroke-engines/me-gi?utm_medium=maxperf&utm_source=google&utm_campaign=campaign_ft_sic_valuechain_240901&utm_term=sic&gad_source=1&gclid=Cj0KCQiArby5BhCDARIsAIJvjIQGvyacsLSRvURpfmqkY-sUFo_b7Kt7wj6a8P0HUJSBTRJd-aEGZUkaAtfrEALw_wcB (accessed on 3 January 2025).
103. Yanmar, A. Study on Combustion Improvement in Dual-Fuel Engine for Biogas Applications. YANMAR Technical Review. Available online: https://www.yanmar.com/global/about/technology/technical_review/2023/12_3.html (accessed on 3 January 2025).
104. Gaikwad, M.S.; Jadhav, K.M.; Kolekar, A.H.; Chitragar, P.R. Combustion Characteristics of Biomethane—Diesel Dual-Fueled CI Engine with Exhaust Gas Recirculation. *Biofuels* **2021**, *12*, 369–379. [CrossRef]
105. Reiter, A.J.; Kong, S.C. Combustion and Emissions Characteristics of Compression-Ignition Engine Using Dual Ammonia-Diesel Fuel. *Fuel* **2011**, *90*, 87–97. [CrossRef]
106. Elkafas, A.G.; Rivarolo, M.; Gadducci, E.; Magistri, L.; Massardo, A.F. Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives. *Processes* **2022**, *11*, 97. [CrossRef]
107. Malik, V.; Srivastava, S.; Bhatnagar, M.K.; Vishnoi, M. Comparative Study and Analysis between Solid Oxide Fuel Cells (SOFC) and Proton Exchange Membrane (PEM) Fuel Cell—A Review. *Mater. Today Proc.* **2021**, *47*, 2270–2275. [CrossRef]
108. Methanol—Price—Chart. Available online: https://tradingeconomics.com/commodity/methanol (accessed on 3 January 2025).
109. Wang, Y.; Pang, Y.; Xu, H.; Martinez, A.; Chen, K.S. PEM Fuel Cell and Electrolysis Cell Technologies and Hydrogen Infrastructure Development—A Review. *Energy Environ. Sci.* **2022**, *15*, 2288–2328. [CrossRef]
110. Hauth, M.; Becker, D.; Rechberger, J. Solid Oxide Fuel Cell—A Key Technology for a Highly Efficient Energy System. *MTZ Worldwide* **2021**, *82*, 58–63. [CrossRef]
111. EUR-Lex. Implementing Regulation—2023/180—EN. Available online: https://eur-lex.europa.eu/eli/reg/2023/180 (accessed on 23 December 2024).
112. Moreno-Gutiérrez, J.; Calderay, F.; Saborido, N.; Boile, M.; Rodríguez Valero, R.; Durán-Grados, V. Methodologies for Estimating Shipping Emissions and Energy Consumption: A Comparative Analysis of Current Methods. *Energy* **2015**, *86*, 603–616. [CrossRef]
113. Winther, M. *Ship Emissions and Air Pollution in Denmark: Present Situation and Future Scenarios*; Danish Ministry of the Environment: Copenhagen, Denmark, 2009.
114. Jalkanen, J.P.; Brink, A.; Kalli, J.; Pettersson, H.; Kukkonen, J.; Stipa, T. A Modelling System for the Exhaust Emissions of Marine Traffic and Its Application in the Baltic Sea Area. *Atmos. Chem. Phys.* **2009**, *9*, 9209–9223. [CrossRef]
115. Wang, C.; Corbett, J.J.; Firestone, J. Modeling Energy Use and Emissions from North American Shipping: Application of the Ship Traffic, Energy, and Environment Model. *Environ. Sci. Technol.* **2007**, *41*, 3226–3232. [CrossRef] [PubMed]
116. Dalsøren, S.B.; Eide, M.S.; Endresen, O.; Mjelde, A.; Gravir, G.; Isaksen, I.S.A. Update on Emissions and Environmental Impacts from the International Fleet of Ships: The Contribution from Major Ship Types and Ports. *Atmos. Chem. Phys.* **2009**, *9*, 2171–2194. [CrossRef]
117. Endresen, Ø.; Sørgård, E.; Behrens, H.L.; Brett, P.O.; Isaksen, I.S.A. A Historical Reconstruction of Ships' Fuel Consumption and Emissions. *J. Geophys. Res. Atmos.* **2007**, *112*. [CrossRef]
118. EUR-Lex. European Union Directive—2018/2001—EN. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L2001 (accessed on 2 January 2025).
119. ClassNK Pathway to Zero-Emission in International Shipping—Understanding the 2023 IMO GHG Strategy. Available online: https://www.classnk.or.jp/hp/pdf/info_service/ghg/PathwaytoZero-EmissioninInternationalShipping_ClassNK_EN.pdf (accessed on 2 January 2025).
120. International Council on Clean Transportation. Accounting for Well-to-Wake Carbon Dioxide Equivalent Emissions in Maritime Transportation Climate Policies. Available online: https://theicct.org/publication/accounting-for-well-to-wake-carbon-dioxide-equivalent-emissions-in-maritime-transportation-climate-policies/ (accessed on 2 January 2025).
121. Calculation of Fuel CO_2 Emissions. Network for Transport Measures. Available online: https://www.transportmeasures.org/en/wiki/manuals/sea/calculation-of-fuel-co2-emissions/ (accessed on 23 December 2024).

122. Oh, J.; Kim, D.; Roussanaly, S.; Lim, Y. Greenhouse gas emissions of shipping with onboard carbon capture under the FuelEU Maritime regulation: A well-to-wake evaluation of different propulsion scenarios. *Chem. Eng. J.* **2024**, *498*, 155407. [CrossRef]
123. Bellot, A.; Baumler, R.; Bouallou, C.; Nemer, M.; Ölcer, A. A cradle-to-grave assessment of carbon and energy footprints of ships using synthetic fuel for net-zeros operations. *Ocean. Eng.* **2024**, *310*, 118392. [CrossRef]
124. Life Cycle Assessment (LCA) for Shipping. Available online: https://www.bergermaritiem.nl/en/life-cycle-assessment-lca-shipping (accessed on 17 January 2025).
125. Applications of Life Cycle Assessment in Shipping. Available online: https://www.researchgate.net/publication/280313533_Applications_of_Life_Cycle_Assessment_in_Shipping (accessed on 17 January 2025).
126. Moreno-Gutiérrez, J.; Durán-Grados, V. Calculating ships' real emissions of pollutants and greenhouse gases: Towards zero uncertainties. *Sci. Total Environ.* **2021**, *750*, 141471. [CrossRef]
127. International Maritime Organisation IMO Framework on Life Cycle GHG Intensity of Marine Fuels (LCA). Available online: https://www.imo.org/en/OurWork/Environment/Pages/Lifecycle-GHG---carbon-intensity-guidelines.aspx (accessed on 2 January 2025).
128. Lloyds Register Availability of E-Fuels and E-Fuel-Capable Vessels. Available online: https://www.lr.org/en/knowledge/research-reports/2024/zemba-report/ (accessed on 2 January 2025).
129. Ozkan, M.; Narappa, A.B.; Namboodiri, T.; Chai, Y.; Babu, M.; Jennings, J.S.E.; Gao, Y.; Tasneem, S.; Lam, J.; Talluri, K.R.; et al. Forging a Sustainable Sky: Unveiling the Pillars of Aviation e-Fuel Production for Carbon Emission Circularity. *iScience* **2024**, *27*, 109154. [CrossRef]
130. Kapetanović, M.; Núñez, A.; van Oort, N.; Goverde, R.M.P. Energy Use and Greenhouse Gas Emissions of Traction Alternatives for Regional Railways. *Energy Convers. Manag.* **2024**, *303*, 118202. [CrossRef]
131. SINTEF SFI Smart Maritime. Available online: https://www.sintef.no/en/projects/2015/smart-maritime/ (accessed on 2 January 2025).
132. EFuel Alliance. Aviation. Available online: https://www.efuel-alliance.eu/political-demands/aviation (accessed on 2 January 2025).
133. Peacock, J.; Cooper, R.; Waller, N.; Richardson, G. Decarbonising aviation at scale through synthesis of sustainable e-fuel: A techno-economic assessment. *Int. J. Hydrogen Energy* **2024**, *50*, 869–890. [CrossRef]
134. Transport & Environment. E-Fuels Observatory for Shipping. Available online: https://www.transportenvironment.org/articles/e-fuels-observatory-for-shipping (accessed on 2 January 2025).
135. Clean Shipping Coalition. Key Design Considerations for GFS and the Basket of Measures. Available online: https://cleanshipping.org/wp-content/uploads/2024/03/ISWG-GHG-16-2-19-Key-design-considerations-for-GFS-and-the-basket-of-measures-CSC.pdf (accessed on 2 January 2025).
136. Sustainable Shipping Initiative. Availability of Sustainable Biofuels. Available online: https://www.sustainableshipping.org/wp-content/uploads/2022/01/Availability-of-Sustainable-Biofuels-Report-updated-final.pdf (accessed on 2 January 2025).
137. EMSA—European Maritime Safety Agency. Update on Potential of Biofuels for Shipping. Available online: https://www.emsa.europa.eu/newsroom/latest-news/item/4834-update-on-potential-of-biofuels-for-shipping.html (accessed on 2 January 2025).
138. IEA. An Introduction to Biogas and Biomethane—Outlook for Biogas and Biomethane: Prospects for Organic Growth—Analysis. Available online: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane (accessed on 2 January 2025).
139. European Commission. Biomethane Country Fiches—Estonia. 2023. Available online: https://energy.ec.europa.eu/publications/2023-biomethane-country-fiches_en (accessed on 2 January 2025).
140. Estonian Biogas Association Estonian Biomethane Roadmap 2030 (2050). Available online: https://www.eestibiogaas.ee/_files/ugd/1f4d17_3ec36a951ceb4b63b3fc429d0fc510a9.pdf (accessed on 2 January 2025).
141. Äripäev. Riik Suunab Biometaani Tootmise Suurendamisse Ligi 20 Miljonit Eurot. Available online: https://www.pollumajandus.ee/uudised/2024/05/30/riik-suunab-biometaani-tootmise-suurendamisse-ligi-20-miljonit-eurot (accessed on 2 January 2025).
142. Lloyds Register. Fuel for Thought Biofuel Report. Available online: https://www.lr.org/en/knowledge/research-reports/2024/fuel-for-thought-biofuel-report/?creative=718481107124&keyword=biofuels%20for%20shipping&matchtype=p&network=g&device=c&utm_source=google&utm_campaign=&utm_medium=cpc&utm_content=&utm_term=biofuels%20for%20shipping&gad_source=1 (accessed on 2 January 2025).
143. ERR. Estonia Aims to Quadruple Use of Green Fuels by 2030. Available online: https://news.err.ee/1609280163/estonia-aims-to-quadruple-use-of-green-fuels-by-2030 (accessed on 2 January 2025).
144. GoodFuels. HVO for Coastal and Inland Shipping. Available online: https://www.goodfuels.com/hvo-coastal-inland-shipping (accessed on 2 January 2025).
145. Abraham, E.J.; Linke, P.; Rawashdeh, M.; Rousseau, J.; Burton, G.; Al-Mohannadi, D.M. Large-scale shipping of low-carbon fuels and carbon dioxide towards decarbonized energy systems: Perspectives and challenges. *Int. J. Hydrogen Energy* **2024**, *63*, 217–230. [CrossRef]

146. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. FuelEU Explainer: Is the Industry Ready for 2025? Available online: https://www.zerocarbonshipping.com/news/fueleu-explainer-is-the-industry-ready-for-2025/ (accessed on 2 January 2025).
147. IEA Bioenergy. Advanced Biofuels—Potential for Cost Reduction. Available online: https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf (accessed on 2 January 2025).