

Article

Evaluation of Alternative Fuels for Coastal Ferries

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Abstract: The International Maritime Organization (IMO) and European Union (EU) have set targets to reduce greenhouse gas (GHG) emissions. Focusing on ships above 5000 GT, their measures exclude several ship types, such as fishing vessels, offshore ships, and yachts. However, smaller ships generate 15–20% of the total GHG emissions. Multiple potential fuel alternatives are already in use or have been investigated to minimize carbon emissions for coastal ferries. This study evaluates the possibility of using alternative fuels for small ferries by seven different parameters: technical readiness, presence of regulations, GHG emission reduction effectiveness (with two different criteria), capital expenditure (Capex), operating expenditure (Opex), and ice navigation ability. The assessment is based on an evaluation of state-of-the-art literature as well as second-hand statistics and press releases. The study also reports the most recent implementations in each alternative technology area. As a result, it was found that although there are several measures with high potential for the future, the most feasible fuel alternatives for coastal ferries would be fully electric or diesel-electric hybrid solutions.

Keywords: GHG emission reduction; coastal ferries; alternative fuels; low carbon



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1. Introduction

The IMO has set a target to reduce total GHG emissions from shipping by 50% worldwide, and the EU is aiming to achieve carbon neutrality in Europe by 2050 [1]. The current focus is on measures such as carbon pricing schemes (ETS) and low GHG fuel standards (FuelEU Maritime) that target ships above 5000 GT. The IMO and EU measures exclude several ship types, such as fishing vessels, tugs, offshore ships, and yachts. However, according to Armstrong [2], smaller ships generate 15–20% of total GHG emissions. This is a significant amount of CO₂ for a carbon-neutral future that should not be kept unregulated.

From a wider perspective, the IMO and EU have similar main goals, but regionally, the EU is aiming for significantly tighter regulations and span. The European Parliament's environmental committee (ENVI) voted in May 2022 to include ships of 400 GT and above in the Emissions Trading System (ETS) [3]. With this implementation, European waters are heading towards maritime decarbonization on a wide scale and the limitations also affect the coastal ferry industry.

Ferry production and operational changes are already being implemented by ship owners all over the world. It should be noted that although there are no valid requirements for smaller vessels, there is currently a need to review the requirements [4] since the market is guiding coastal ferries towards becoming carbon neutral. It can be claimed that in the coastal ferry industry, there is a chance to reduce GHG emissions and a desire and initiative is also in place. The market and trends are changing, and many potential fuel alternatives are under development or already in use by smaller crafts.

Apart from alternative fuels, other measures, including slow steaming, main engine de-rating, waste heat recovery, and changes in operational patterns, can be applied to decrease

CO₂ emissions. These measures are not new in the shipping industry and were initially implemented to reap benefits such as minimized operational costs and fuel consumption [5]. In addition to low GHG emissions, slow steaming has drawbacks for political reasons and its direct impact on trade [6]. Similarly, main engine de-rating has been offered by most engine producers, but also has limited use depending on the climate and ice conditions. On the other hand, engine de-rating in certain regions with warm climates creates additional GHG emission reduction possibilities [7].

In order to achieve climate goals, it is necessary to make immediate decisions when planning policies to retrofit existing fleets and build new ships.

Since the most significant effect on reducing emissions is provided by using alternative fuels, this study aims to answer the following significant research questions: What are the current alternative fuel systems for new coastal ferries in planning and under construction? Which of these systems has the most significant potential for use considering today's technical developments, legislation, ability to reduce GHG emissions, and the economic environment?

The goal of this work was to study the usability of various present-day alternative fuel systems with existing technologies or technologies in high R&D stages. The focus of the study is to analyze GHG emission reduction directly related to the ship's energy use. The origin of the fuel is not considered in this study.

Section 2 presents the work of Lindstad et al. [8], which is the basis for our analysis of coastal ferries. Section 3 presents a general overview of the ages of the vessels and possibility of using alternative fuels or other GHG emission reduction measures, as well as an overview of different alternative fuel pilot projects and an evaluation of the potential technologies that could be applied to coastal ferries. Future developments and how they can be predicted and summarized based on the ratings are discussed in Section 4. The conclusions of the study are presented in Section 5.

2. Assessment of Alternative Fuels

When comparing alternative fuels, recent studies have mainly assessed the entire life cycle of an energy carrier using the LCA (life cycle assessment) method, which covers the whole chain of use starting from fuel extraction and ending with combustion in the internal combustion engine of the ship. In the past, studies investigating the use of fuels have mainly dealt with three different stages: Well-to-Tank (WTT), Tank-to-Wake (TTW), and Well-to-Wake (WTW), the latter of which combines the first two.

Unlike the WTW method, the full LCA method also includes the construction and decommissioning of the fuel production chain. Lindstad et al. [8] mapped 22 alternative pathways for using fuels in the maritime sector and compared the qualitative and quantitative factors. Aspects were weighted based on their impact, considering that they have complex relationships with GHG emissions, technical readiness, economic profitability, safety, and industry regulations. As a result of the study, they concluded that in the short term, the most economically efficient energy usage model for reducing GHG emissions was the use of fossil fuels in combination with CCS (carbon capture system) installation, which increased costs by approximately 18% compared to conventional marine fuels. Additionally, conventional fuels with CCS and biodiesel required fewer volumes than the other alternatives and required minimal modification to the existing infrastructure. The most energy-efficient option was using electricity, which would reduce energy consumption by 27–50%. Hydrogen and ammonia needed the highest energy for production but emitted zero carbon and particulate emissions [9].

Lindstad et al. [8] used the concept of E-fuels (electro-fuels) in categorizing an emerging class of carbon-neutral fuels that are produced by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels. For shipping, liquid hydrogen and ammonia are the two main E-fuels generated from the same starting point: water electrolysis into hydrogen and oxygen. Hydrogen and ammonia manufacturing is feasible for shipping, but the fuels must be liquefied. However, liquid hydrogen needs cryogenic

conditions and liquid ammonia needs low-temperature storage at $-33\text{ }^{\circ}\text{C}$, or alternatively, both require pressurization to 350–700 bars, which are too space demanding for most shipping applications. Thus, the use of these fuels doubles or triples the maritime sector's energy consumption in a Well-to-Wake context.

The second entry in this category is synthetic E-fuels (synthetic electro-fuels), gaseous or liquid fuels produced from hydrogen and carbon captured from the air using renewable electricity. Having high energy efficiency, synthetic E-diesel is fully compatible and blendable with MGO (Marine Gasoil), and synthetic E-LNG (Electric-liquefied natural gas) is fully compatible and blendable with E-diesel or LNG and E-LNG. Additionally, these fuels do not require new infrastructure or bunkering facilities in ports, unlike ships fueled on hydrogen or ammonia [8].

According to McKinlay et al. [10], hydrogen has more potential than ammonia and methanol because its green production process has fewer losses. Additionally, hydrogen production requires less upscaling (171%) of manufacturing to meet the global fleet's energy demands. Unlike other modes of transport, shipping inherently operates with more fuel on board than is ever likely to be used for a single voyage; this is especially true for HFO (heavy fuel oil) storage. Therefore, reducing storage levels closer to the expected output can reduce mass and volume requirements and make alternative fuels significantly more viable.

Since short-distance shipping journeys are naturally shorter, and it is possible to switch to energy supply chains in at least one port, local shipping is also moving without existing regulations to energy solutions with low GHG emissions, such as electricity and hydrogen.

3. Decarbonizing Coastal Ferries

According to Equasis [11], the world's passenger ship fleet consisted of 7567 vessels in 2020.

The age composition of the fleet in Table 1 indicates that 53% of all passenger ships are 25+ years old and should be replaced soon. For this research, it is essential to look at small and medium-sized ships, where decisions will be made shortly to replace nearly 3900 vessels aged 25+ years as the time resources of the ship begin to be exhausted. It is estimated that these ships account for up to 20% of the global GHG emissions attributed to shipping.

Table 1. World passenger fleet size in 2020. Source: Authors' own compilation, based on data from Equasis [11].

Age/Size	Small ⁽¹⁾		Medium ⁽²⁾		Large ⁽³⁾		Very Large ⁽⁴⁾		Total	
0–4 years old	348	9%	371	9%	32	2%	32	2%	783	10%
5–14 years old	595	5%	559	4%	58	1%	66	2%	1278	17%
15–24 years old	778	9%	555	7%	100	3%	75	5%	1508	20%
+25 years old	2491	8%	1405	8%	91	16%	11	6%	3998	53%
Total	4212	56%	2890	38%	281	4%	184	2%	7567	100%

⁽¹⁾ GT < 500; ⁽²⁾ 500 ≤ GT < 25,000; ⁽³⁾ 25,000 ≤ GT < 60,000; ⁽⁴⁾ GT ≥ 60,000.

Det Norske Veritas (DNV) has created the Alternative Fuels Insight platform [12], according to which the total number of existing and ordered new passenger ships (including cruise ships, RoPax, and car/passenger ferries) using alternative fuel solutions or GHG emission reduction devices (CCS) is 788 (see also Table 2).

Table 2. Passenger ships in service and on order. Source: Authors' own compilation, based on data from DNV [12].

Vessel Type	LNG	LNG-Ready	Scrubber	Battery	Hydrogen	Methanol	Total
Ferries	53	4	13	289	4	0	363
RoPax	33	9	95	7	0	1	145
Cruise ships	35	0	223	21	1	0	280
Total	121	13	331	317	5	1	788

Comparing the Equasis [11] and DNV [12] databases, 10.4% of the existing passenger ships and vessels that will be built soon already use or will use alternative fuels. The focus of this study is smaller (less than 5000 GT) car/passenger ferries, which account for nearly 50% of all vessels with alternative fuel use.

There is a clear trend in the energy use of smaller passenger ferries. In newly built vessels, the focus is on electricity use in cooperation with electricity storage technologies. Figure 1 shows the precise distribution of alternative energy solutions among car/passenger ferries. The data reflected in the figure is derived from the DNV Fuel Insight [12] portal as of June 2022 and includes both ships in operation and those to be built in the future.

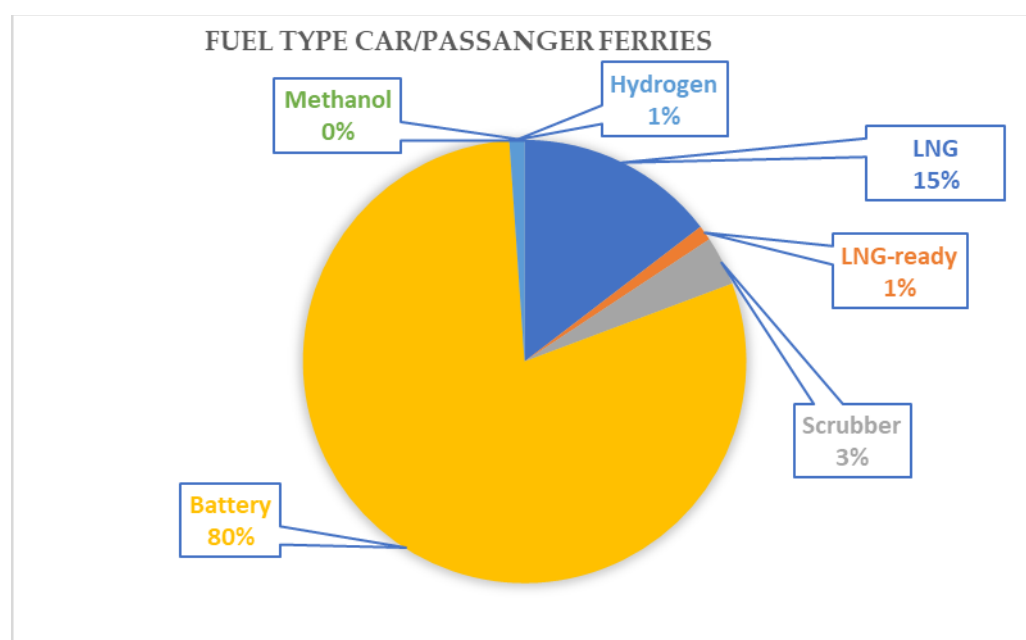


Figure 1. Car/passenger ferries in operation and on order [12].

My Word displays percentage sum 100% as follows: battery 80%, LNG 15%, scrubber 3%, hydrogen 1%, LNG-ready 1%. For clearance, Figure 1 in picture format is added.

Different battery solutions are used in 289 out of 363 ships, i.e., nearly 80% of cases. Approximately 15% of vessels use LNG as the primary energy source, and the remaining 5% of ships use other energy sources (see details in Table 3).

In 2022 and later, batteries will be installed on 69 ships as a retrofit or new construction. In terms of energy use, there are 30 hybrids, 15 plug-in hybrids, and 24 fully electric ships. They are geographically divided, with 6 ships in the USA, 35 ships in Asia, 26 ships in Europe, and rest are in unknown locations.

Table 3. Energy solutions for Car/passenger ferries in operation and order. Source: Authors' own compilation, based on data from DNV [12].

Type	In Operation	In Order
LNG	46	7
Scrubber	13	0
Hydrogen	2	2
Batteries	220	69
<i>Pure electric</i>		24
<i>Hybrid</i>		30
<i>Plug-in hybrid</i>		15

3.1. Fuel Alternative Pilot Projects with the Most Potential

A literature review and analysis of various low-emission alternatives was conducted for this study. Despite the lack of environmental regulations for coastal ferries, there are abundant modifications available on the market for vessels to lower their emissions. The development and interest in carbon-free ferries are apparently rising, and each sector of the maritime industry can contribute, from leisure yachts to large cargo vessels (without exemptions).

3.1.1. Diesel-Electric Hybrid

The highest number of newbuilt or retrofit examples currently have diesel-electric hybrid systems. Examples of newbuilt coastal ferries include the Uber Boat [13] in the UK; the Arlau, Alster, and Stecknitz in Germany [14]; and the Ibestad in Norway, which is a retrofit motor ferry (MF) [15].

Another significant aspect for fully electric coastal ferries in northern areas of the Baltic Sea is the ice conditions and cold temperatures [16]. This challenge is only met by the Elektra in Finland (a hybrid electric ferry) through the use of supportive diesel engines in winter conditions, which serve the vessel in cases of traveling through the ice. Therefore, it should be noted that diesel-electric hybrids are most likely the best alternative for cold conditions.

While assessing the current use of fully electric and diesel-electric hybrid alternatives, it is essential to clarify the geographical location [17], infrastructure of ports, and the electrical supply's limitations. In several cases of finalized newbuilt vessels, the port's readiness to supply the vessel with electricity is insufficient. A similar issue is a concern for remote areas and smaller islands, where the electrical supply and infrastructure are outdated and capacities are not built to fulfill the demands of sizeable external electricity users. For those cases, it is essential to evaluate the life-span of a vessel and assess the risks of using only fossil fuels if the infrastructure is not ready to supply electricity. Having onboard electrical batteries is another factor that raises fuel consumption, first due to the extra weight and second due to limited cargo or passenger capacity on board for the exact dimensions of the ship.

3.1.2. Fully Electric

Fully electric, battery-powered systems are an excellent option for shorter distances and milder climates. The first fully electric car and passenger ferry was the MF Ampere in Norway [18]. This ferry a remarkable example of not emitting greenhouse gases and having exceptionally low noise levels during operation. The first large e-ferry, the Ellen [19], operates in Denmark and should be noted for the same benefits.

Similar innovative developments have been carried out to build the first high-speed craft with zero emissions. The TrAM project [20] vessel, the Medstraum, began its operation in Norway in 2022.

When focusing on fully electric fuel options, the biggest challenge is currently the battery's physical size, capacity [21], and price [22]. For leisure vessels, battery price is also a disadvantage, but it is expected that price reduction will take place with technology development in time and significant changes in battery innovations [23]. On the other hand, a great advantage for such vessels is their operational noise levels.

3.1.3. Hydrogen

Norway has taken the lead in hydrogen use in transportation; therefore, it is not a surprise that they have also built and put into operation the first hydrogen MF, the Hydra [24].

The first hydrogen-powered commercial ferry, the Sea Change [25] (Projects—SW/TCH Maritime, n.d.), was launched and operates in San Francisco Bay. Moreover, with similar characteristics, the first CTV (crew transfer vessel), the Hydrocat 48 [26], is operating in the UK.

It also must be noted that the future is promising for the current storage and infrastructure issues [27]. Other means of transportation are interested in hydrogen use, which helps to develop areas that still lack opportunities and cost-effectiveness. As for other fuel alternatives, use of hydrogen as a fuel varies in countries and regions. Hence there are several promising methods of hydrogen production. For example, in specific locations in Canada, hydrogen is produced from the waste heat of nuclear power plants [28].

3.1.4. Methanol

For longer distances and larger vessels, the focus seems to be heading towards methanol. In 2015, the Stena Germanica was a hybrid of diesel or methanol fuel use, but the vessel has run on recycled methanol since 2021 [29].

Although methanol has a lot of potential, the current significant issue is that it is widely dependent on price dynamics in different regions, according to Masih et al. [30]. On the other hand, it is also essential to include that several large shipping companies, such as Maersk [31] and Cosco [32], have found methanol as a key factor for minimizing GHG emissions.

3.1.5. Liquefied Natural Gas

Another fuel alternative that has gained wide popularity for longer distances and larger ferries is liquefied natural gas (LNG). With this alternative, it is essential to note that the use of LNG itself does not decrease GHG emissions [33] and there is no significant CO₂ reduction. Nevertheless, it is considered to be the cleanest fossil fuel.

An example would be the RoPax Salamanca [34], the first LNG-fueled passenger ferry to operate from the U.K. Successful LNG retrofit examples include the German ferries MS (motor ship) Ostfrieslan and MS Münsterland [35]. There are also diesel-LNG hybrids, such as the MS Megastar [36].

The hybrid solution enables a reduction in operating costs while gas pricing and availability are unstable. LNG use greatly depends on the region and regional policies [37]. The instability of gas prices was one of the most significant benefits of LNG usage before Europe's energy crisis in 2022. Among the disadvantages of LNG usage, an essential factor to consider is the risk of methane leakage and methane slip [38]. Similar to electric batteries, there are several technical and dimensional implementation issues with using LNG as fuel oil [39].

3.2. Evaluation of Potential Technologies

This research assessed the possibility of using alternative fuels on small coastal ferries by evaluating seven parameters, as shown in Tables 4 and 5. The assessment's color scale is divided into five parts (see rating map). Red indicates a rating of 0, meaning a situation that essentially excludes the use of the solution, whereas green indicates a rating of 4, which means that full readiness already exists for the solution. The sum of the ratings indicates

the success of the technology's usability. Table 5 shows the numerical values, including the average, median, and standard deviation.

Table 4. The potential of alternative fuels in coastal shipping. Source: Authors' composition.

	Technical Readiness	Regulations	Zero Emission		Capex	Opex	Ice	Rating
			Well-to-Tank	Tank-to-Wake				
Plug-in hybrid			If non fossil source					26
Hybrid			If non fossil source	No grid energy				25
LNG	Methane slip		Fossil	Methane slip				23
Pure electric			If non fossil source		Bat. cost			23
Scrubber	CO ₂ ; CH ₄ ; N ₂ O		Fossil	CO ₂ ; CH ₄ ; N ₂ O				20
Methanol	Safety	Passenger	If non fossil source					19
Hydrogen			If non fossil source					18
Ammonia	Poisonous	Passenger	If non fossil source					16
Rating map								
	0							
	1							
	2							
	3							
	4							

Table 5. Numeral ratings of alternative energy systems in coastal shipping. Source: Authors' composition.

	Technical Readiness	Regulations	Zero Emission		Capex	Opex	Ice	Rating (Total)	Average	Median	St. Deviation
			Well-to-Tank	Tank-to-Wake							
Plug-in hybrid	4	4	3	3	4	4	4	26	3.71	4.00	0.49
Hybrid	4	4	3	2	4	4	4	25	3.57	4.00	0.79
LNG	2	4	2	3	4	4	4	23	3.29	4.00	0.95
Pure electric	4	4	3	4	2	4	2	23	3.29	4.00	0.95
Scrubber	2	4	0	2	4	4	4	20	2.86	4.00	1.57
Methanol	2	2	3	4	2	2	4	19	2.71	2.00	0.95
Hydrogen	4	4	3	4	0	1	2	18	2.57	3.00	1.62
Ammonia	0	0	3	4	2	3	4	16	2.29	3.00	1.70

The different parameters are described as the following:

- **Technical Readiness:** Evaluates the existence and use of relevant technologies in commercial use now. For example, manufacturers do not offer solutions without methane emissions for LNG systems. Scrubber technologies have been designed to reduce SO₂ and are not currently optimized to catch GHG, such as carbon dioxide, methane, and laughing gas, nitrous oxide. In the case of methanol, there are no workable solutions for the safe storage of fuel onboard passenger ships. In the case of ammonia, human safety due to the extreme toxicity of the gas needs to be addressed.
- **Regulations:** Assesses the current situation regarding the regulatory status of the use of the technology and the possibility of use with passengers on board the ship (IMO, [40]).
- **Zero emission Well-to-Tank:** Assesses the production process and supply of the fuel used by the ship based on the GHG emissions of the cycle and its compliance with the agreed climate targets. As many fuels can use both fossil fuels and renewable energy sources, the technology depends on the fuels available in the region and the choice of ship operator [9].
- **Zero emission Tank-to-Wake:** Illustrates the impact of the ship's potential GHG emissions and compliance with agreed climate goals.
- **Capex (Capital Expenditure):** Indicates the estimated size of the investment compared to the share of today's usual assets in the business model [41].
- **Opex (Operative Expenditure):** Estimates the running costs of the technology, such as fuel and technical maintenance, compared to today's habitual costs as a share of the business model [42].
- **Ice:** Appreciates the possibility of using the technology in more severe ice conditions, which need remarkably more propulsion power and onboard energy storage.

The option with the highest rating (26 points) was the plug-in hybrid system. The range of fuels in this system is diverse, and shipping will move in this direction regardless of the development activities that take place in the future. The system earned the maximum results (see Table 5) both in the “Technical Readiness” and “Regulations” categories because this solution is already in actual use. Smaller battery systems of up to 1000 kWh are already being installed quite widely today, and shore-based automatic charging systems are also in commercial use. The maximum results in the “Capex” and “Opex” categories were based on the fact that the costs of the system are already approaching market conditions (covering peak loads) compared to fossil fuels, and the system in this form can be successfully used in winter ice conditions.

The system allows for full carbon-free energy use when e-fuels or synthetic e-fuels are used as fuels in internal combustion engines. The electricity produced from renewable energy is also used in shore-based electricity systems. Nevertheless, lower scores (3 points) were achieved in both “Zero emission” categories because e-fuel production opportunities are lacking or are economically uncompetitive for commercial use today [43]. Additionally, the onshore electricity supply is based mainly on non-GHG emission-free sources.

A hybrid system achieved the second highest rating result (25 points). Like the plug-in hybrid system, there is an opportunity to achieve carbon neutrality using e-fuels with existing technology. At the same time, a lower rating (2 points) was achieved in the “Tank-to-Wake” category because it misses the charging option offered by advanced power grids from shore-side systems. Therefore, more considerable bunker reserve or denser bunkering is required by land transport, which raises the traffic load of fuel trucks on port roads.

In the evaluation model, LNG (23 points), as a low-carbon energy solution, achieved identical results as the pure electric solution. However, current market trends (see Tables 2 and 3) clearly show that problems with the use of LNG (methane slip as reported by Gronholm et al. [44] and Seithe et al. [45]) have significantly reduced the usage of LNG in new construction projects. Therefore, the system earned 2 points in the “Technical Readiness” category. The lower result in the “Well-to-Tank” category (2 points) was caused by the fossil fuel nature of the system and that in the “Tank-to-Wake” category (3 points) was because the system is not completely emission-free in its current development.

In contrast, fully electric solutions achieved the same result as LNG in the total ratings (23 points). Unfortunately, as a large part of light transport moves in the direction of electricity use, there may be a significant shortage of electricity supply, especially in remote areas and islands where mainland electricity connections are built without sufficient capacity reserves. The lower result for the “Capex” category (2 points) indicated the high installation cost for a sufficient battery capacity on board. The same result in the “Ice” category (2 points) reflected current difficulties using the system in harsh ice conditions, where the energy reserve on board with existing battery systems is insufficient for safe navigation.

The scrubber, a currently widely used cleaning system combined with HFO, received 2 points in the “Technical Readiness” and “Tank-to-Wake” categories because this technology is mainly optimized for reducing air pollutants such as SO_x and NO_x emissions and not for GHG such as CO₂ (carbon dioxide), CH₄ (methane), and N₂O (nitrous oxide “laughing” gas). Since these systems are commonly built to collaborate with fossil fuels, the results in the “Well-to-Wake” category were the lowest possible—0 points.

Methanol, as a fuel, achieved a total score of only 19 points, even though it is generally considered promising as a marine fuel. Although there are technical solutions for using methanol as fuel, the system requires almost 2.5 times more ship space for both fuel storage and technical handling [46]. In addition, in today’s solutions, methanol is not used as the only fuel, which means that two alternative systems are needed on board small coastal ferries, which reduces the useful space. Although the IMO has regulated fuel use, systems have not yet been installed on smaller passenger ferries, and domestic regulations do not yet favor relatively toxic fuel in passenger shipping. Partly due to the reasons above and based on the fact that there is no ground-based methanol infrastructure for scaled fuel production, the system received only 2 points in the “Technical Readiness,” “Legislation,”

“Capex,” and “Opex” categories. The “Well-to-Tank” category received 3 points because currently, methanol is mainly produced from fossil fuel-based feedstocks [10].

The main reasons for the low overall result for hydrogen (18 points) as a fuel were the low points received in the “Capex” (0 points) and “Opex” (1 point) categories. At today’s prices, the system cost (Capex) of various solutions used with hydrogen fuel is 2 to 2.5 times higher than that of a diesel system. According to forecasts, hydrogen (Opex) will not become price competitive with diesel until 2050 [47]. The low result in the “Ice” category (2 points) was based on the fact that the most significant critical factor for hydrogen systems is the space required for fuel storage [48]. When navigating difficult marine conditions, the amount of fuel stored would be unreasonably high for coastal ferries.

In median terms (see Table 5), the first five options performed equally well (from plug-in hybrid to scrubber). However, the scrubber displayed considerable variation (st. dev.) and should not be considered in this high-performing group. Despite this, the scrubber should not be excluded either; it was between the lowest three groups and the highest group (and very close to the latter).

Each of the lowest three solutions are troublesome in some respects. For example, the methanol option had a high average performance and slight variation. However, its median performance was the lowest in this evaluation (it received ratings of 2 in many aspects, and only a few high ratings of 4).

Hydrogen and ammonia had standard deviations in their performance that were too high, very low ratings (with ratings of 0 in many aspects), and they do not seem feasible or they have apparent weaknesses.

At the high end of this evaluation, it could be said that the plug-in solution was the highest performing in the group, even considering the average and standard deviation. However, the hybrid solution followed it very closely.

4. Discussion

Currently, the market, and not legislation, is indicating that coastal ferries should become carbon neutral, and the market is heading towards minimizing GHG emissions. Statistics on newly built and under-construction vessels show that each fuel has several alternatives with specific advantages and disadvantages. Nevertheless, the coastal ferry business is generally heading towards diesel-electric hybrids and fully electric energy solutions.

There are multiple potential alternative fuels to decrease the GHG emissions of coastal ferries (see e.g., Balcombe et al. [49]; Bouman et al. [50]; and Korberg et al. [51]). There are options for using LNG, batteries, methanol, LPG (liquefied petrol gas), hydrogen, and ammonia. In addition, there are other alternatives to reduce GHG emissions in ferries, for example, slow speeding, main engine de-rating, waste heat recovery, and changes in operational patterns. Lindstad et al. [8] evaluated their costs and emissions.

Statistics [12,52] on newbuilt and under-construction vessels and ratings obtained in this research showed that the ferry business is mainly heading towards diesel-electric hybrids, plug-in hybrids, and fully electric energy solutions. The range of usable fuels in these systems is diverse.

A coastal ferry with a diesel-electric propulsion system is the most attainable alternative with minor requirements for the operator and infrastructure. Diesel is necessary for emergencies and more challenging conditions, such as ice and low temperatures.

Regardless of what will be the fuel solution of the future, it can already be estimated that shipping will move to zero-carbon energy use when (1) e-fuels or synthetic e-fuels are used as fuels in internal combustion engines, and (2) electricity produced from renewable energy is supplied to ships from shore-based electricity loading systems.

It is essential that existing solutions also allow Nordic countries to ensure necessary navigation in difficult ice conditions. Despite achieving a high rating by LNG as a low-carbon energy solution, current market trends show that problems with methane slip have significantly reduced the usage of this solution in new ship building projects.

In contrast, all-electric solutions have become prevalent on smaller passenger ferries in inland waters and navigation areas without ice conditions. It is also essential to consider the following: as a large part of light transport moves in the direction of electricity use, there may be a significant shortage of electricity supply, especially in remote areas and islands where mainland electricity connections are built without sufficient capacity reserves.

It was found in this study that hydrogen, methanol, and ammonia are very promising fuels in shipping. However, the technical solutions and regulatory framework for passenger transport using ammonia as fuel are currently lacking. In addition, using methanol is in the developing stage, primarily for cargo shipping. In contrast, in the case of hydrogen, the biggest obstacle is the system's construction and operating costs. Additionally, ignorance of future tax levels for grey or green hydrogen significantly increases investment risks in hydrogen systems. For these various arguments, it was found that at this point, the most feasible solutions for coastal ferries in the near future would be fully electric- or diesel-electric hybrid-powered solutions.

Compared to earlier studies of alternative fuels, this study provides new information about smaller coastal ferries operating on short routes and near external energy sources, which means less need for onboard fuel storage. In addition, the usability of alternative energy systems in conditions of ice navigation is assessed.

The limitation of this work was the availability of technical data. Due to large-scale innovations in the field, market participants hide accurate technical information due to competition or share generalized information, which complicated the analysis. The implementers of different fuel technologies narrowly exchange information with organizations in their field, and so-called information in energy research is not found in any database. Therefore, essential arguments may have been sufficiently overlooked in the analysis. Research for finding measures to decarbonize coastal ferries continues. In further research, case studies of more specific environments will be carried out with more apparent solutions and actions that could be taken to achieve carbon neutrality in the region.

5. Conclusions

Lowering GHG emissions for small vessels and coastal ferries in European navigating areas is currently being initiated by shipbuilders, shipowners, and operators. The development and interest in carbon-free ferries are apparently rising, and there will be more feasible solutions in the future.

This study assessed the possibility of using alternative fuels on small ferries by seven different parameters, including technical readiness, presence of regulations, GHG emission reduction effectiveness (with two different criteria), Capex (capital expenditure), Opex (operative expenditure), and ice navigation ability.

There are several fossil fuel alternatives. As a result of this study, it was found that currently, the most suitable solution would be to use fully electric or diesel-electric hybrid solutions. The use of heavier fossil fuels, such as Low-Sulfur Residue Marine Fuel, in cooperation with scrubbers has clear potential, but the impact of asphaltenes on fuel stability [53], their potential for use in emission control areas [54], and their impact on lubrication systems must be taken into account in future studies.

In the near future, it is expected that changes in logistics, infrastructure, and science will offer alternatives that are more competitive in the market. It is also evident that the availability of different fossil fuel alternatives varies in different regions. While focusing on the ferry industry, it is essential to consider regional peculiarities and opportunities for specific lines. This study aimed to provide a general perspective, and research should focus on specific regions, fleets, and ferry lines and their best-suited fossil fuel alternatives in future studies.

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