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Review

CO₂ Emissions Reduction Measures for RO-RO Vessels on Non-Profitable Coastal Liner Passenger Transport

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Abstract: Reducing CO₂ emissions from ships in unprofitable coastline transport using electricity and hydrogen has potential for island development to improve transport and protect biodiversity and nature. New technologies are a challenge for shipping companies and their introduction should be accompanied by a system of state aid for alternative energy sources. The energy requirements of an electric ferry for a route of up to 6 km were considered, as well as the amount of hydrogen needed to generate the electricity required to charge the ferry batteries to enable a state aid scheme. For a daily ferry operation, a specific fuel consumption of 60.6 g/kWh of liquid hydrogen is required in the system fuel cell with a total of 342.69 kg of hydrogen. Compared to marine diesel, the use of electric ferries leads to a reduction of CO₂ emissions by up to 90%, including significantly lower NO_x, SO_x, and particulate matter (PM) emissions, and operating costs by up to 80%.

Keywords: CO₂ emissions; e-ferry; hydrogen; state aid; sustainable maritime transport



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1. Introduction

The growth of maritime connectivity, based on the introduction of new technologies and ship designs, is an ancient maritime tradition, just as connecting islands to the mainland [1]. However, the shipping industry contributes significantly to global greenhouse gas and other pollutant emissions [2].

Shipping generates a variety of pollutants that lead to a variety of problems [3]:

- The main greenhouse gas (GHG) emitted by ships is carbon dioxide (CO₂). GHG emissions are the main cause of global warming.
- Acid rain is caused by sulfur oxides (SO_x) and nitrogen oxides (NO_x), both of which are highly undesirable because of their effects on human health.
- Human health is harmed by carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM) [4].

While there is more and more talk about renewable energy sources, greenhouse gas emissions continue to rise year after year, given the increasing mobility of all citizens and population growth. According to the European Environment Agency, greenhouse gas emissions have been rising steadily since 2014, increasing 29% from 1994 to 2018 [5].

Road transport is the source of most greenhouse gas emissions; in 2018, road transport accounted for 77% of total greenhouse gas emissions [6]. In contrast to road transport, greenhouse gas emissions from shipping are much lower, peaking in 2008 and then falling by almost 25% by 2015. The economic recession that followed the 2008 crisis was largely responsible for the decline, as was the improvement in energy efficiency. Since 2015, emissions have been gradually increasing again and amounted to 146 Mt CO₂ in 2017, which is still 20% lower than in 2008 [7,8].

Today, the shipping sector highlights the problem in terms of pollution from ships, but also in terms of tons of treated water discharged into the sea or into certain reception facilities such as port reception facilities for ships' ballast water, bilge water containing oil, etc.

According to the Third International Maritime Organization (IMO) Greenhouse Gas Study, maritime transport contributes around 940 million tons of CO₂ per year, or about 2.5% of global greenhouse gas emissions [9]. If no immediate action is taken to reduce emissions, the International Maritime Organization predicts that this figure will rise to as much as 15% by 2050 [10]. The exact amount will be determined by the future social and economic situation. However, emissions from shipping will increase in all scenarios. Global warming and the maritime sector are directly related to the Intergovernmental Panel on Climate Change (acronym IPCC), a United Nations-based intergovernmental body based in Geneva. In 1988, the IPCC established the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO). The IPCC publishes reports based on a coordinated research program of several thousand experts in more than a hundred countries. These highlight that climate change is accelerating, is man-made, and increases the risk of war and conflict due to already scarce natural resources. (e.g., drinking water) and that urgent countermeasures must be taken to prevent a global climate crisis and threats to humanity's livelihoods.

The state aid program for services of general economic interest grants compensation to shipowners for unprofitable ferry services. At the same time, the EU's green plan requires a reduction in CO₂ emissions and secures additional green state aid for unprofitable coastal passenger services. The aim of this paper was to investigate the state of the art in green coastal shipping, which today is based on electric propulsion where energy is stored in batteries, and then to evaluate an equivalent hydrogen-based alternative solution. Electric ferry lines up to 6 km in length were considered, as they are the most likely candidates for environmentally friendly coastal ferry lines in the Adriatic Sea. When electricity is used for ship propulsion, two problems must be solved: the storage of energy on board and the infrastructure to supply energy on land. In both cases, environmentally friendly solutions exist simultaneously. As far as onboard storage is concerned, electricity can be stored in batteries or in hydrogen, which is used by fuel cells to generate electricity. As for onshore infrastructure, there should be a power grid to recharge the batteries or, alternatively, a stable supply chain to store and deliver hydrogen. While the performance of all-electric coastal shipping is relatively easy to evaluate, the hydrogen-based alternative requires additional attention.

Both the article and the literature cite the general advantages of using hydrogen: emission-free technology, rapid transfer of fuel from shore to ship, the possibility of a noncombustible type of storage. The use of hydrogen is particularly feasible on the Adriatic Sea due to the availability of natural resources for hydrogen production. To estimate the required fuel consumption and consequently the required green state aid, an all-electric ferry operating in Norway was used as a study case. For the same vessel running on hydrogen, about 342 kg of hydrogen is needed per day. This can be compared to 5 to 6 MWh of electricity required daily by an all-electric ferry. The article points out that hydrogen produced by electrolysis is the cleanest of all fuels studied in [11], while the total CO₂ emissions for all-electric propulsion depend heavily on the method of production.

2. EU Concession in Coastal Liner Passenger Transport

With the accession of the Republic of Croatia to the European Union the *acquis communautaire* became legally binding in the Republic of Croatia. Articles 107, 108, and 109 of the Treaty on the Functioning of the European Union are the laws of the EU on state aid [10]. The procedure is standardized in most countries, and a public tender is held, in which the shipowner may apply for a concession to run a shipping company, and if the tender finds that the line is unprofitable, the line for which the state receives a certain amount of state funds is to assist in connecting the island with the mainland.

To ensure a regular connection of the islands to the mainland, the public transport system should be provided even if it is not profitable, compensating the shipowner for the provision of a public service.

2.1. EU Framework for Concession in Coastal Liner Passenger Transport

State aid is defined in Article 107 as any existing or planned government expenditure or revenue foregone that distorts or threatens to distort competition by conferring a particular advantage [12]. The European Commission, in collaboration with the Member States, supervises all state aid schemes in the Member States and determines, in line with Article 108, whether the state aid initiative is compatible with the internal market.

In accordance with the Lines Act and Occasional Coastal Maritime Transport, a public transport system was set up to ensure regular connections between the inhabited islands and the mainland and between the inhabited islands with enough daily connections in both directions to create better living conditions on the islands. State lines are determined and defined by the Government Decision on the establishment of state lines in public transport in coastal line transport. On state lines where the revenue from the provision of services cannot cover the costs incurred in fulfilling the public service obligation (unprofitable lines), state aid is granted to shipowners in the form of public service compensation. The Agency for Coastal Liner Passenger Transport authorizes state aid in the Republic of Croatia (hereinafter: The Agency).

Competence to apply Commission Decision 2012/21/EU of 20 December 2011 on the application of Article 106(2) of the Treaty on the Functioning of the European Union to State aid in the form of public service compensation granted for the provision of services of general economic interest (hereinafter: SGEI package). Financial support from the state may be necessary to cover all or part of the specific costs arising from the SGEI obligation, as granted to certain undertakings [13]. The Decision concerns compensation granted to shipowners entrusted with the operation of services of general economic interest within the meaning of Article 106(2) of the Treaty, which falls within the category of compensation for services of general economic interest. In the two financial years preceding the year in which the service of general economic interest is provided, the average annual traffic should not exceed 300,000 passengers ([14] "From Review of Maritime Transport 2020, by United Nations Conference on Trade and Development, ©(2021, United Nations. Used with the permission of the United Nations.").

The importance of the Member State in the implementation of the EU acquis ensures a safe and harmonized implementation policy where the EU Green Plan should reduce CO₂ emissions and ensure green state aid for unprofitable scheduled passenger transport in coastal shipping.

2.2. Example in the Republic of Croatia

The main task of the Ministry of Finance is to carry out and supervise the implementation of the state aid policy within the framework of fiscal measures. The state aid program for services of general economic interest in the form of public service compensation is submitted to the Ministry of Finance for an opinion on whether it complies with the guidelines of the state aid policy and the fiscal policy of the EU and the Republic of Croatia. The budget for the allocation of the state aid is the Croatian kuna, HRK 310,000,000 in the state budget of the Republic of Croatia for 2017, HRK 305,000,000 for 2018, and HRK 305,000,000 for 2019 [15].

It is likely that to reduce CO₂ emissions, an additional measure to subsidize and reward green ships will need to be introduced to meet IMO and EC targets. Subsidizing alternative fuels for unprofitable passenger traffic in coastal shipping should continue to be a flag state obligation to preserve islands and the sea.

3. New Technologies in Short-Sea Shipping

Each year, maritime transport moves about 11 billion tons of shipping containers, solid, liquid, and bulk goods across the world's waters [16]. There used to be little environmental oversight of shipping companies and ports, but accidental oil spills in the 1960s led to widespread coastal pollution and seabird deaths, leading to the creation of the International Convention for the Prevention of Pollution from Ships (MARPOL) [17]. MARPOL is the international convention for the protection against pollution from ships [18]. The application of new technologies and alternative fuels, as well as shipbuilding technologies, will ensure a clean and safe environment for future generations.

3.1. Pollution and Environmental Protection from Ships

Despite the fact that the International Maritime Organization (IMO) employs a variety of mechanisms to protect the marine environment from shipping operations, maritime traffic continues to have harmful effects. Marine protected areas (MPAs) play an important role in protecting and conserving our global marine ecosystems [19]. The history and development of MPAs is highlighted worldwide, from their beginnings to the current level of protection and through globally recognized progressive goals related to marine conservation.

The key role of MPAs in the future for ocean protection is highlighted, addressing the following issues: Increasing the ocean's resilience to climate change, particularly CO₂, protecting global fisheries, effectively managing the ocean, and reducing cumulative negative impacts in general [20].

MPAs are currently applied in over 66 countries (44% of nations with seawater) and span six continents and four ocean basins. The penalties prescribed for pollution from ships are felt most by users of passenger transport, i.e., the cruise industry [21].

European Union (EU) investment in research and development, particularly programs such as the Sixth Framework Program (FP6), Horizon 2020, and others, have led to the possibility of developing ships with electric propulsion [22,23]. It is well known that ships and ports are crucial for the economic development of any coastal country. However, they also pose certain environmental challenges due to their environmental impact and social standards. Emissions from ships are monitored by drones used by port authorities and safety inspectors, while at EU level they are monitored by EMSA—the Lisbon-based European Maritime Safety Agency [24].

Use of GHG Assessment

The International Maritime Organization (IMO) is responsible for regulating the global shipping industry. The Energy Efficiency Design Index (EEDI), which came into force in 2013, is an IMO regulation that mandates an increase in the energy efficiency of ships and applies to many of the world's largest vessels [25]. The EEDI mandates that new ship designs become more energy efficient the EEDI requires new ships to emit less CO₂ per unit of "transport work," typically described as g CO₂/(DWT*Nm). Ships built between 2015 and 2019 are required to be 10% more efficient than the baseline of ships built between 1999 and 2009. Subsequently, ships built between 2020 and 2024 must be 20% more efficient, and those built in 2025 or later must be 30% more efficient than the baseline [26].

The aim of the EEDI is to create equal opportunities for comparison, to encourage the construction of more efficient ships in general, and to set minimum efficiency levels for new ships depending on ship size and type.

In April 2018, at the 72nd session of IMO's Marine Environment Protection Committee (MEPC), a GHG strategy was adopted and can be summarized in three points [27]:

1. Reduce carbon emissions from ships by implementing further phases of the EEDI for new ships.
2. Reduce CO₂ emissions per transport job by at least 40% by 2030, with a target to reduce them by 70% by 2050 (compared to 2008 levels).
3. Reduce annual GHG emissions by at least 50% by 2050, with the aim of reducing GHG emissions from international shipping as soon as possible (compared to 2008).

The assessment of greenhouse gas compares the relative efficiency of a ship using the Existing Vessel Design Index (EVDI) or Energy Efficiency Design Index (EEDI). The Energy Efficiency Design Index (EEDI) was created as a regulatory tool to minimize CO₂ emissions and improve the operational efficiency of ships during the ship design process. Comparison of comparable groups is based on the number of EVDI ship standard deviations from the average for similar sized ships of the same ship type. Ship efficiency is determined by the ratio of grams of CO₂ emissions per ton and nautical mile [28].

Ship efficiency is determined using data from one of two sources: EEDI—a regulation developed by the IMO for new ships (and applicable to existing ships) or EVDI—a rating system developed by Right Ship that can be applied to new and existing ships (where EEDI is not available or applicable). The relative performance of the ships is rated from A to G. The most efficient ships receive a rating of A, the least efficient is a rating of G [29].

Although the greenhouse gas assessment is relatively simple to interpret, the methodology for calculating the greenhouse gas assessment is relatively complex. The IMO Marine Environment Protection Committee (MEPC) resolution on the EEDI is summarized in Table 1 [30].

Table 1. The International Maritime Organization (IMO) description of the various Energy Efficiency Design Index (EEDI) parameters [30].

Parameter	Description
fj	A correction factor used to adjust for ship-specific design features (e.g., shuttle tankers, ice classed ships)
PME	75% of the main engine MCR (Max. Continuous Rating)
CFME and CFAE	Conversion factor between fuel consumption and CO ₂ emissions for the main engine that is non-dimensional.
SFCME	In g/kWh, the main engine's certified specific fuel consumption
PAE	Auxiliary engine power
SFCAE	In g/kWh, the main engine's certified specific fuel consumption
PPT (i)	75% of the shaft motor's rated power consumption
feff (i)	Availability factor of innovative energy efficiency technology
PAEeff (i)	Reduced auxiliary power as a result of new electrical energy-saving technologies.
Peff (i)	At 75% main engine power, output of unique mechanical energy efficient technology for propulsion
fi	Correction factor to account for ship-specific design elements (e.g., shuttle tankers and ice class ships)
fc	Correction factor for cubic capacity (for gas carriers and chemical tankers)
fl	Factor for general cargo ships with cranes and other cargo-related equipment to compensate for the ship's loss of deadweight.
Capacity	1. For passenger vessel: gross tonnage (GT) 2. For cargo and oil tankers: computed as a function of deadweight as specified in MEPC 245(66) "2014 Guidelines on the Calculation of the Attained EEDI for New Ships" in Sections 2.3 and 2.4.
fw	In a realistic sea condition of wave height, wave frequency, and wind speed, a non-dimensional coefficient showing a drop in speed.

Vessels may only be compared to other vessels of similar size and of the same vessel type. Comparison of comparable groups is based on the number of standard deviations of the vessel's EEDI or EVDI from the average for similar sized vessels of the same vessel type.

Figure 1 shows the bell curve indicating the percentage distribution by the corresponding letter in the colored area below the curve [29]. The x-axis is expressed by the number of standard deviations that correspond to the result of the quantity in the key.

As an example, 176,382 tons of bulk cargo has a GHG rating of D, with a size rating of D—0.345. It is considered together with ships with plus or minus 10% of its carrying capacity, putting it in the range of 158,744 to 194,020 carrying tons. Since there are 1060 vessels

in the comparison group in this case, about 735 are more efficient and 325 are less efficient than the observed vessel [29].

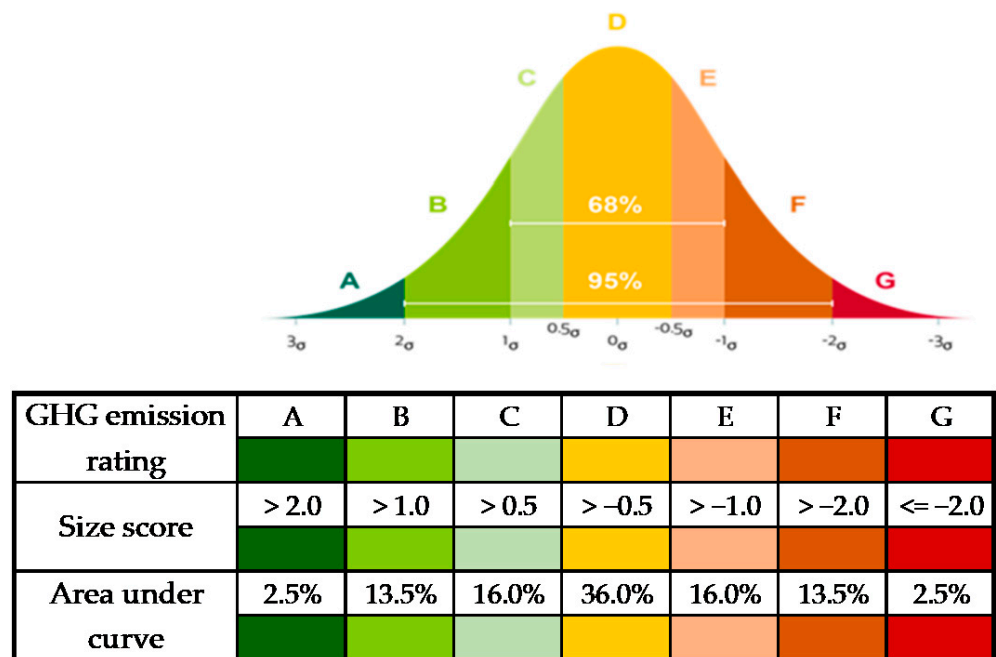


Figure 1. Greenhouse gas (GHG) Emissions Rating Key—Normal Peer Distribution [29].

It is also important to note that in November 2020, IMO adopted amendments to MARPOL, Annex VI, at the Marine Environment Protection Committee 75th Session by introducing an Energy Efficiency Design Index for Existing Ships (EEXI) [31].

The proposed measure, known as the EEXI, is an energy efficiency index for current ships based on the EEDI methodology that applies technical efficiency standards. The EEDI limits carbon intensity only for newly built ships, while the EEXI would limit CO₂ emissions per unit of transport supply rather than per unit of transport work [32].

3.2. Reduction of CO₂ Emissions with Hydrogen

Ship pollution awareness is constantly growing, and the influence of digital media and social networks is leading to the rapid application of regulatory frameworks aimed at reducing and controlling emissions from ships. The objective to increase the energy efficiency of ships in order to reduce emissions of SO_x, NO_x, CO₂, and PM (MARPOL Annex VI) leads to the introduction of new technologies [33]. For many years, the main fuel used in shipping was a heavy fuel oil, but with electric and hybrid ships entering the market, the understanding of ships has changed.

The ongoing diversification of marine fuels and advances in energy efficiency have significant implications. Figure 2 shows a scenario based on a forecast of future maritime fuel consumption and increased energy efficiency, as well as a Lloyds Registry estimate of heavy fuel oils (HFOs) and liquefied natural gas (LNG) market share. The biggest force reducing the need for low sulfur fuel is the increase in power from the old fleet, which equates to an extra 110 or so “negatonnes” of fuel, which is almost 24% of the forecast demand [34].

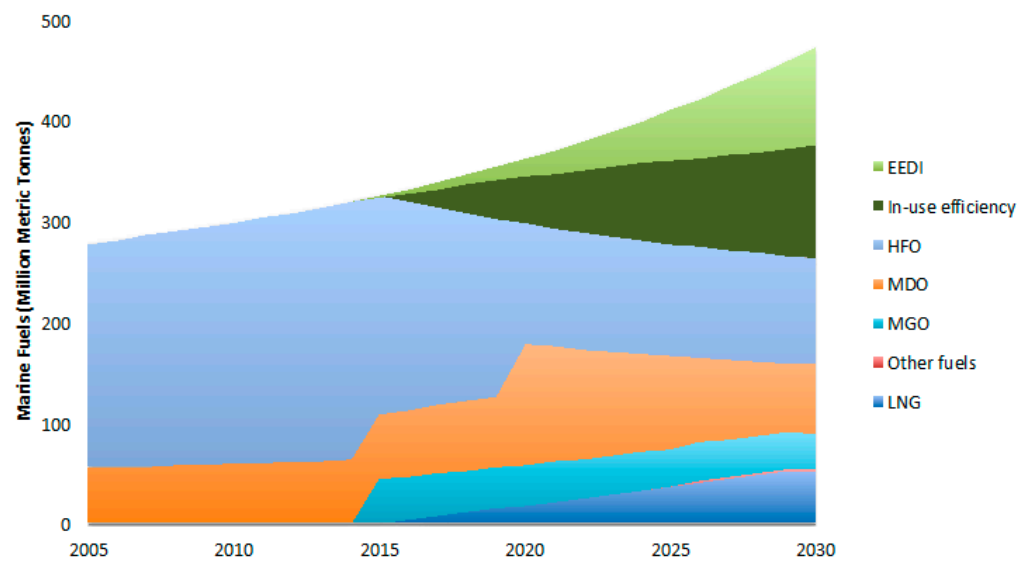


Figure 2. Marine fuel use over the period 2005–2030 [34].

HFOs combined with EEDI, scrubbers, and distillates are estimated results, each accounting for about 20% of total fuel consumption in the graph. LNG is expected to triple its market share between 2020 and 2030. Renewables, fuel cells, and biofuels are expected to have a tiny market share in 2030.

Residents of developed countries prefer to travel by electric high-speed trains and hybrid ships. They use multimodal transportation to avoid using their own cars, thus saving money, but also reducing CO₂ emissions. The development of new electric and hybrid ships leads to the need for new forms of alternative energy sources, their development and use, and their integration into the so-called multimodal transport network.

Hydrogen storage in ports can be applied or transported in shipping containers to improve intermodality, which includes advanced maritime transport. Compressed hydrogen can be used as a fuel instead of diesel for charging electric ferries in island ports that are inaccessible for further subsea investment to lay power cables. Hydrogen is an indirect fuel for an electric ferry as hydrogen can generate electricity.

Examples of using alternative energy sources to generate electricity to reduce CO₂ emissions are islands such as the Galapagos, Mauritius, Orkney Island, and others [35–38].

The research, prepared by Andrea A. Eras-Almeida et al., aimed to reduce fuel consumption and energy generation costs to promote the Galapagos Zero Fossil Fuel Initiative and Sustainable Development Goal 7. To this end, HOMER Pro, a specialized hybrid renewable mini-grid planning tool, was used to perform many techno-economic analyses focusing on different electricity demand scenarios [36].

Alternative solutions offered include the use of photo panels, biodiesel (sugar cane), and green hydrogen, a product of the electrolysis of water using electricity from ocean currents [39]. Some changes that are taking place in Orkney, for example, need to be included and linked to the move to a greater proportion of renewable energy. One of these changes is the inclusion of marine energy use, which includes wave and tidal power as well as hydrogen and electrolysis, which have shown promising test results for future exploration [38]. Figure 3 is a flow chart showing the process of storage, production, and potential use of hydrogen in Orkney. Surf 'n' Turf wants to take the program, which is tied to the use of hydrogen, to a higher level in the future and use it to fuel ships. To accomplish this in the future, they are training crew members to safely use alternative fuels.

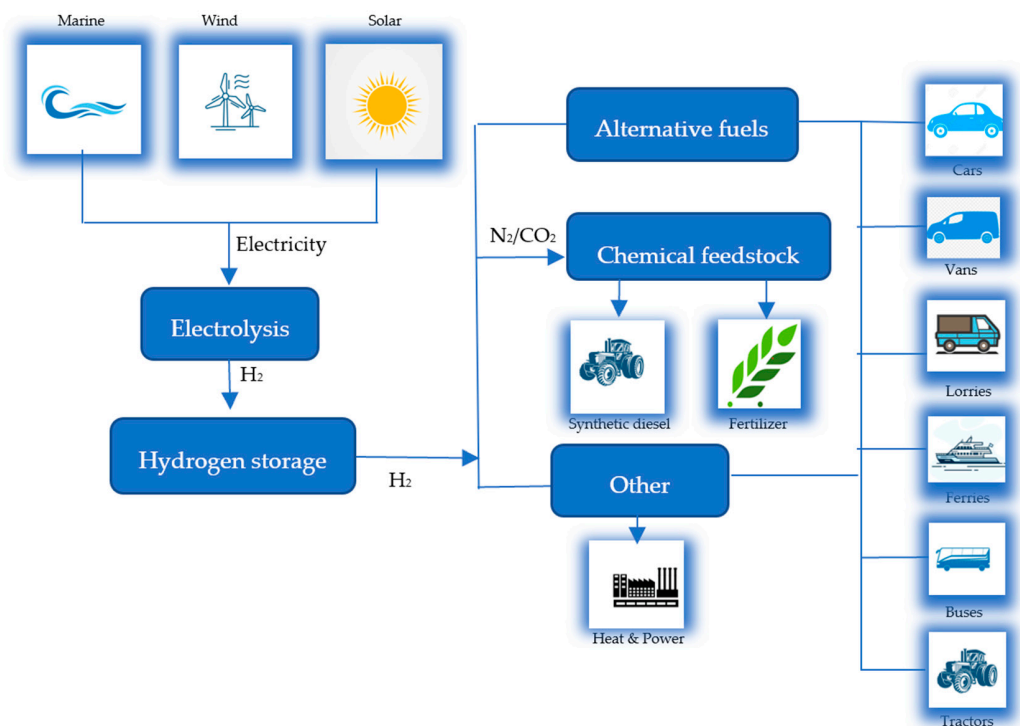


Figure 3. Hydrogen production, storage, and potential uses in Orkney [40].

3.3. Introduction of State Aid for Alternative Fuels on Non-Profitable Lines in Coastal Liner Passenger Transport

Main and auxiliary engines, which can be divided into diesel engine, gas turbine, steam turbine, and electric motor, generate the necessary energy on board ships. Due to its low fuel consumption compared to other propulsion engines, the diesel engine is the most used main propulsion engine on merchant ships. The smallest high-speed engine has a power of 0.25 MW, while the largest low-speed marine diesel engines have a power of up to 100 MW [41].

Diesel fuels have different advantages. Due to their technical advantages, diesel engines are preferred in shipping. Experts claim that diesel fuel performs better than gasoline because the exhaust gases are less likely to burst or burn during operation. It is claimed that diesel fuel is more efficient than gasoline because it contains 10% more energy per gallon than gasoline. Unlike gasoline engines, diesel engines do not require a spark to start. Large ships prefer diesel engines because they are less risky when carrying a large amount of fuel at sea. Compression ignition diesel engines are preferred by several international shipping companies [42].

Fuel cells and hydrogen, as new technologies, can make influential reductions in emissions from ships compared to diesel and gaseous fuels of fossil origin (natural gas and liquefied natural gas). Carbon dioxide (CO₂) is one of the basic products of combustion and is non-toxic but is associated with the “greenhouse effect” and global warming. Today, more and more attention is being paid to protecting the atmosphere from the emission of harmful exhaust gases. Burning fossil fuels releases sulfur dioxide, carbon dioxide, and nitrogen oxides into the atmosphere, which contribute significantly to pollution. The emission of harmful exhaust gases from marine engines is limited by international and national regulations of individual countries, especially those that are more polluted with harmful exhaust gases due to the higher concentration of maritime traffic. In passenger coastal shipping, electric ferries have proven fuel savings of 80% and emission reductions of up to 95% [43]. However, green energy does not always mean clean energy; in the United States, for example, most electricity is generated from non-renewable sources such as fossil fuels. In fact, electricity generation is the leading industrial source of air pollution

in the U.S., emitting more CO₂ than any other industry and accelerating the effects of climate change. Clean energy, on the other hand, does not pollute the environment in any way [44]. The subsidy of electricity as a base fuel relative to diesel can be analyzed by determining the energy required for a distance up to 6 km with a typical ferry for such a connection.

The Republic of Croatia uses a variety of energy conversion methods. Nuclear power plants, such as Krsko Nuclear Power Plant, are one of the cleanest types of energy conversion. It is important to note that hydroelectric power plants account for more than half of the power plants in the Croatian power grid. Croatia has 17 large storage and flow-through hydropower plants, about 20 smaller hydropower plants (0.5 to 10 MW) and many mini (0.1 to 0.5 MW) and micro hydropower plants (from 5 to 100 kW). HPP Zakuac is the largest hydropower plant in the country [45].

According to its creators, the first all-electric ferry in Norway is showing impressive results. They also developed an electric propulsion and battery system that provides the ferry with a battery capacity of over 1 MWh [46]. Figure 4 shows a simplified one-line diagram of Norled's MF Ampere all-electric battery ferry with two charging stations and batteries, which is also installed in Oppedal and Lavik. To avoid overloading the city's power grid when the ferry is charging its batteries, there is an energy storage unit on each side of the ferry crossing that is charged during the trip [47,48].

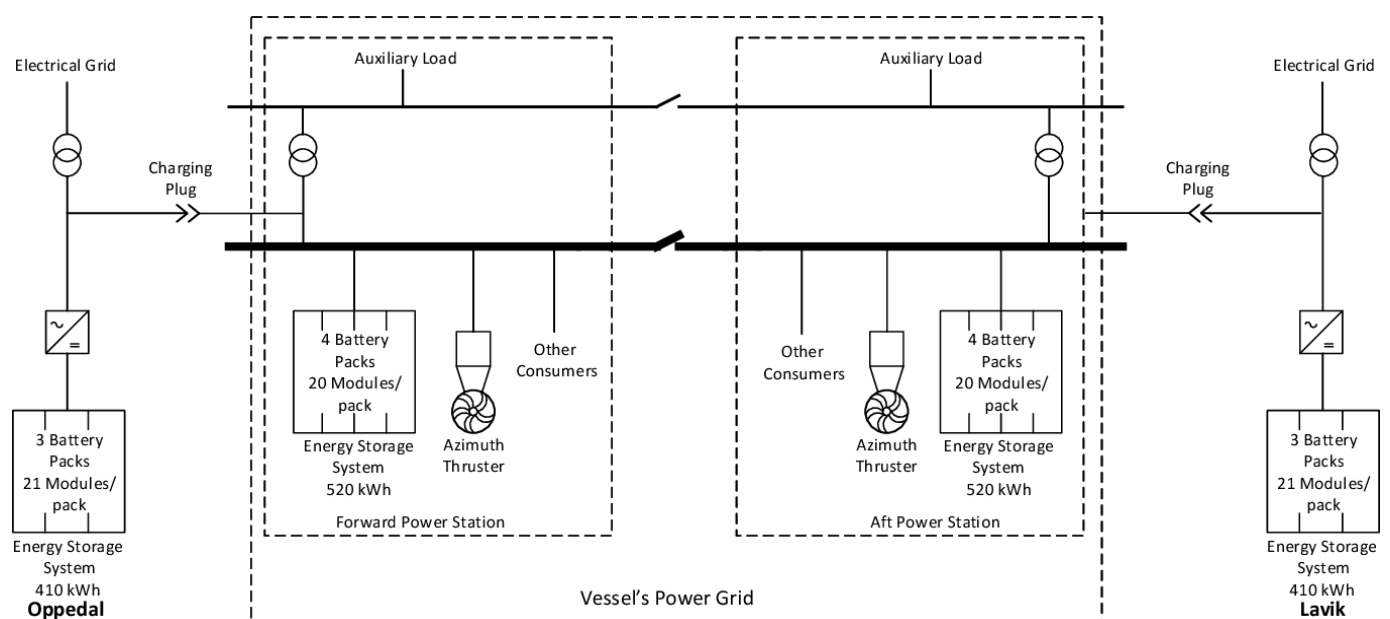


Figure 4. A simplified one-line diagram of the ferry's power system used in Oppedal and Lavik [47].

In particular, this electric ferry has 95% lower emissions and 80% lower costs compared to conventional ships [43]. The ferry, named Amper, was launched in May 2015 with the aim of reducing NO_x and CO₂ emissions and noise pollution. Table 2 shows the main specifications of the Amper line in Norway [49].

For the introduction of state aid and the electrification of ferry lines with up to 20 min at speeds of 10–12 knots, up to 6 km of navigation, the electricity demand is 5–6 MWh per day following the example of an existing ferry.

Specific fuel consumption may be estimated as Equation (1) [50]:

$$SFC = \frac{1}{\delta * \eta}. \quad (1)$$

Table 2. Main specifications of the Ampere line in Norway [46].

Shipowner	Norled
Lenght of the ship [m]	80.8
PAX	360
Battery capacity [MWh]	1
Speed [knots] and distance [km]	10–12 and 6
Transition time [min]	20
Electricity per transition [kWh]	150
Calling port	34

Here δ is the energy density of the fuel in [kWh/g] and η is the overall efficiency of the system. The energy density of the hydrogen is 0.033 kWh/g and an overall system efficiency of 0.5 is assumed, resulting in $SFC = 60.6$ g/kWh.

Based on the energy requirements listed in Table 3, a total of $5654.9 \times 0.0606 = 342.69$ kg of hydrogen is required daily for an operating ferry, assuming a specific fuel consumption of 60.6 g/kWh of liquefied H_2 in the system fuel cell (Table 3) [40]. A land-based refueling station or barge with two tanks at 350 bars with a total capacity of 342.69 kg would meet the daily demand for the consumption of the electric ferry.

Table 3. Hydrogen in relation to the power of a marine engine [44].

Number of days in service per year	355
Calling port	34
Single trip distance [NM]	3.08
Engine power [kW]	900
Percentage of engine used in sailing [%]	60
Speed of sailing [knot]	12
Single trip power consumption [kWh]	166.3

Due to the low density, it is possible to develop a hydrogen storage technology with tanks at 700 bar pressure, which could reduce the amount of hydrogen stored to one tank. LOHC (Liquid Organic Hydrogen Carrier) allows hydrogen to be stored in an organic liquid or a special type of oil, which makes the hydrogen non-flammable and stored at atmospheric pressure and has quantitatively up to three times the possibility of storage in a tank of the same mass. Using hydrogen as a fuel can help reduce greenhouse gas emissions while improving air quality and reducing noise levels. Therefore, with the support of the European Commission, hydrogen is increasingly finding its way into all modes of transport and entering the European Union market.

3.4. Developments under Current Trends

Guidelines for states implementing the EU initiative Green Deal or a similar initiative to introduce new maritime technologies such as hydrogen and ammonia or forms of renewable electrical energy needed to recharge RO-RO vessels fully and rapidly must include state aid as a measure to introduce new green technologies for unprofitable liner coastal shipping.

Measures to comply with the previously mentioned Article 107 of the Treaty on the Functioning of the European Union already include state aid for part of the fossil fuel price for ships connecting islands in the EU; therefore, the technology change must include a “State aid measure for MWh per nautical mile” represented by the ship’s need for a specific dedicated maritime connection [51].

Figure 5 shows that according to current trends and policies (the so-called “base-line scenario”), oil will continue to be the primary source of energy for transportation, despite its progressive decline. The impact of CO₂ emission requirements for new cars, light commercial vehicles (LCVs), and heavy commercial vehicles (HCVs) on the overall efficiency of the vehicle fleet, as well as improvements in the efficiency of the transport system, are expected to reduce energy consumption in the transport sector, excluding international maritime transport, by about 24% by 2050 compared to 2005. Electric cars are expected to account for about 14% of the total vehicle fleet by 2030 and 54% by 2050, with light-duty vehicles accounting for 11% by 2030 and 45% by 2050. Natural gas in the form of compressed natural gas (CNG) and liquefied natural gas (LNG) is expected to be increasingly used in road freight and maritime transport from 2020 onwards [52].

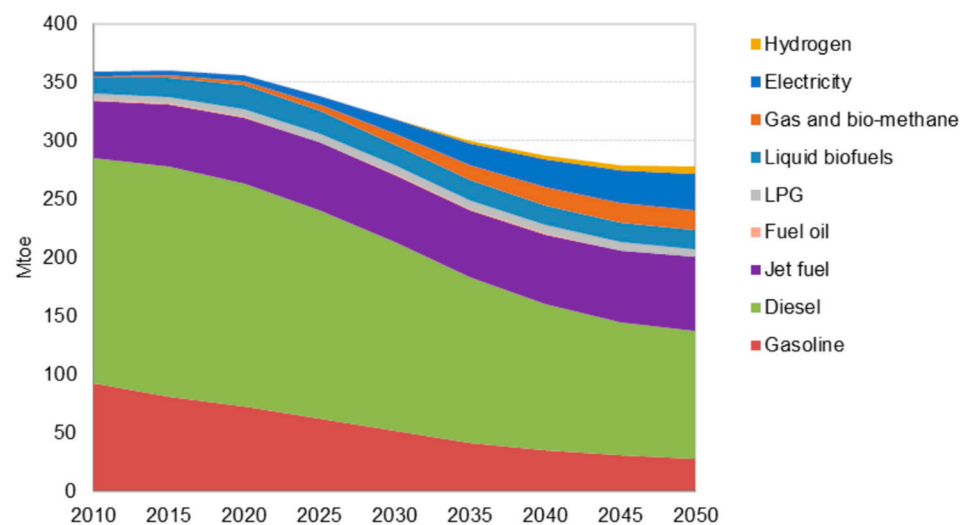


Figure 5. Future trends in the use of different forms of energy [52].

The growing interest in alternative fuels and the goals and policies of many governments around the world are fueling the desire to gradually reduce CO₂ emissions. The latest assessment of the most promising alternative marine fuels available today was published by Det Norske Veritas Germanischer Lloyd (DNV GL) [53]. According to DNV GL, most of the carbon-intensive marine fuels accessible today are methanol, which is derived from methane and has potentially higher net CO₂ emissions than heavy fuel oil and hydrogen, which are all derived from methane. Hydrogen produced by electrolysis has been shown to be the cleanest of the fuels studied, as shown in Figure 6.

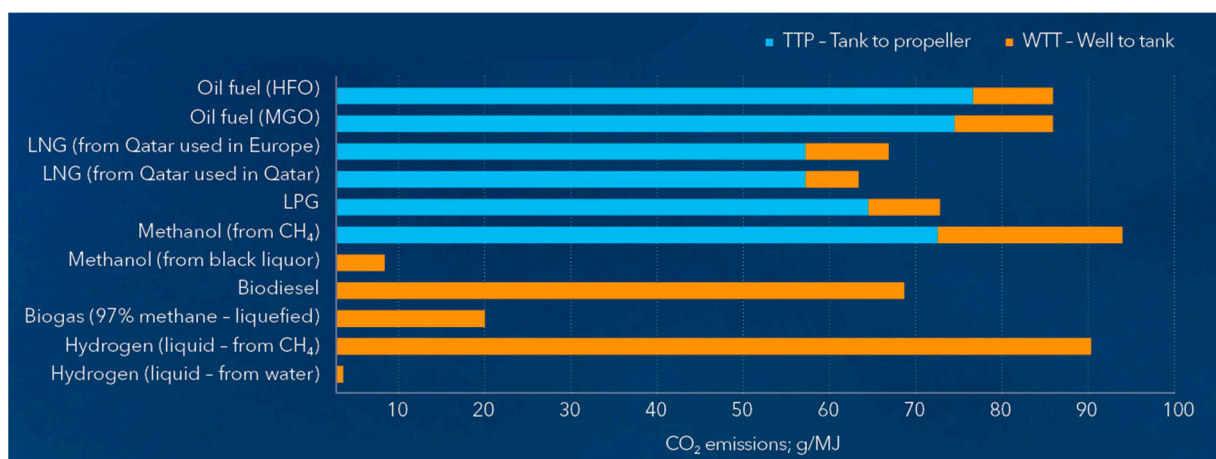


Figure 6. CO₂ emissions of fuel alternatives in shipping [11].

To make unprofitable coastline passenger transport environmentally friendly, there is an urgent need to improve sea links, reduce bottlenecks, and protect NATURA 2000 areas. Sensitive and secular areas where the generation of electrical energy to power the ship might come from hydrogen, ammonia, batteries, or the like, must receive state aid in the transitional period until green technology meets an economic balance of demand and supply.

4. Discussion and Conclusions

The ship as an entity that navigates the sea and performs work tasks for the purpose of connecting the island with the mainland and vice versa, as well as transporting passengers and cargo, can be characterized as an industrial polluter. Due to many regulatory frameworks, shipowners are forced to invest in technologies that are still relatively unprofitable from a financial point of view, but from an environmental point of view, new hybrid and electric-powered vessels in coastal shipping are the first necessity to reduce global warming.

There is a significant number of short coastal ferry lines around the world which, because of the public interest, must provide passenger transport regardless of their profitability. As fuel cell technology matures, an assessment of government support should be undertaken. The article provides a comparative analysis between all-electric and hydrogen-powered mid-size ferries on short ferry routes. The presented research gives an estimation of government support for short coastal ferry routes in terms of hydrogen consumption, for both high season and low season. Specific short Croatian ferry routes are listed as candidates for the application of zero emission hydrogen technology.

The introduction of electric ferries and hydrogen fuel, which generates electricity to charge batteries on electric ferries, is possible through the application of existing technologies. Compared to marine diesel vessels, electric ferries lead to a reduction of CO₂ emissions by up to 90%, including significantly lower NO_x, SO_x, and PM emissions, and operating costs by up to 80%. In Croatia, green hydrogen power generation could be used for the needs of ferry lines Prizna-Žigljen, Stinica-Mišnjak, Brestova-Porozina, Biograd-Tkon, Zadar-Preko and other lines with a travel time of up to 20 min, 5.6 MWh daily power consumption, and a vehicle capacity of 100 to 120 cars. Daily state aid to the ship owner varies between 300–350 kg of hydrogen in high season and 200–250 kg of hydrogen in low season on unprofitable coastal shipping lines.

Due to the availability of natural resources for hydrogen production, the use of hydrogen in the Adriatic Sea is particularly feasible. To estimate the required fuel consumption and government subsidy, an all-electric ferry in Norway was used as a case study. The same vessel running on hydrogen requires about 342 kg of hydrogen per day. This can be compared to the 5 to 6 MWh of electricity needed per day for an all-electric ferry. The article points out that hydrogen produced by electrolysis is the cleanest of all fuels studied and that the total CO₂ emissions of all-electric propulsion depend strongly on the production method.

The use of hydrogen as a fuel can make a significant contribution to reducing greenhouse gas emissions, as well as improving air quality and reducing noise. Therefore, with the support of the European Commission, hydrogen is increasingly finding its way into all modes of transport and entering the European Union market. A very high percentage of miles traveled on ferry lines used to connect sparsely populated and remote islands is unprofitable but necessary to achieve sustainability and normal living conditions on these islands. Many companies in the Mediterranean face these problems, e.g., Croatia, Greece, Italy, etc. Most ferry lines would not be profitable without government subsidies, which are determined based on concessions. The planned use of ships that draw their propulsion energy from various forms of renewable energy sources, such as electricity and hydrogen, reduces costs and CO₂ emissions.

Of course, future research should consider the amount of fossil fuels consumed and the CO₂ emissions generated in the production of equivalent electricity and the hydrogen

needed to maintain coastlines. The trend of advances lies in electricity storage technology, the successful discovery of new materials for battery manufacture, and the recognition that the focus of global industry development is on more efficient forms of renewable energy. It is very safe to assume that some companies not currently profiting from the use of various forms of renewable energy, especially hydrogen, will gain far greater benefits and new insights into the use of green energy in the future than their competitors who are currently focused on short-term profits.

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