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Techno-economic assessment of alternative marine fuels for inland shipping in Croatia

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Abstract

Emissions reduction targets are pushing the shipping industry towards cleaner and more energy-efficient solutions. One option proposed is to replace conventional marine fuels with cleaner fuels. This is particularly important for vessels engaged in short-sea shipping and inland waterway transportation because their exhaust gases more negatively affect the local population than long-distance ships do. Hence the aim of this study is to undertake a technical, environmental and economic analysis of alternative fuels to reduce the environmental footprint and lifetime costs of inland waterway transportation. The analysis will focus on Croatia whose existing outdated inland waterway fleet needs to meet the goals of the Low-Carbon Development Strategy of the Republic of Croatia. In the study, a life-cycle analysis and life-cycle cost assessment of different alternative fuels will be performed taking into account the operating profiles and technical characteristics of vessels working in Croatia. The potential effects of a carbon tax are also examined in a case study considering carbon emissions reduction targets in Croatia by 2030. The electrification of ships is highlighted as the most environmentally friendly option for each considered ship, reaching a carbon emission reduction of up to 51%, while the most cost-effective option varies for each ship.

Keywords: inland waterways; carbon emissions; carbon tax; alternative fuels; life-cycle analysis

Word Count: 8592

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Nomenclature

Variables

AC	annual exploitation costs (€)
B	breadth (m)
BC	battery capacity (kWh)
CA	carbon allowance (€/t CO_2)
DWT	deadweight (t)
E	emission (kg)
EC	energy consumption (kWh/km)
EF	emission factor (g emission/kg)
FC	fuel consumption (kg/km)
IC	investment cost (€)
L	length overall (m)
l	length of one-way trip (km)
$LCCCC$	life-cycle carbon credit cost (€)
$LCFC$	life-cycle fuel cost (€)
LM	lifetime mileage (km)
N	number of round trips (-)
n	time of a ship lifetime (year)
NCV	net calorific value (kWh/kg)
NPV	net present value (€)
P	Power (kW)
PR	price (€)
r	discount rate (%)
SFC	specific fuel consumption (kg/kWh)
t	operational time (h)
TE	tailpipe emission (g emission/kg)
x	share of a fuel (%)

Greek letters

η	efficiency
ρ	density (kg/l)

Abbreviations

AM	Ammonia-powered vessel
BD	B20-powered vessel
CF	Carbon Footprint
CP	Current policies
D	Diesel-powered vessel
E	Electric-powered vessel
GHG	Greenhouse Gas
GWP	Global Warming Potential
H	Hydrogen-powered vessel
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Assessment
LNG	Liquefied natural gas
M	Methanol-powered vessel
NT	Non-taxation
PEM	Proton Exchange Membrane
PTW	Pump-To-Wake
RES	Renewable Energy Source
SD	Sustainable Development
SP	Stated policies
WTP	Well-To-Pump
WTW	Well-to-Wake

Subscripts

A	annual
AE	auxiliary engine
AM	ammonia-powered vessel
ave	average
CR	cracker
D	diesel-powered vessel
E	electric-powered vessel
f	fuel used in a power system
FC	fuel cell
H	hydrogen-powered vessel
i	emission
LNG	LNG-powered vessel
M	methanol-powered vessel
ME	main engine
n	year of a ship lifetime
ot	one-way trip
$P\text{-}f$	pilot fuel mixed with fuel f
$P\text{-}LNG$	pilot fuel in LNG-powered vessel
$P\text{-}M$	pilot fuel in the methanol-powered vessel
PR	purifier

1. Introduction

The exhaust gas released by fossil fuel combustion negatively affects the environment, and is comprised of sulphur oxides (SO_X), nitrogen oxides (NO_X), carbon monoxide (CO), particulate matter (PM), but also Greenhouse Gases (GHGs), whose increased concentration in the atmosphere causes global warming [1]. These latter emissions relate to the emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases in very low concentrations [2]. In the international shipping sector, about 70% of total emissions occur within 400 km of land, which impairs the air quality of coastal areas [3]. Current research into air pollution caused by the shipping sector mainly focuses on seagoing vessels and less on inland waterway vessels whose impact, however, is not negligible, since inland navigation vessels operate along the waterways and directly impair the air quality of the nearby population [4].

Inland waterway transport represents a mode of transport where passengers and freight are transported by vessels via inland waterways (canals, rivers, lakes, etc.) [5]. In contrast to rail and road transport, inland waterway transport offers a sustainable and environmentally friendlier mode of transport, especially in terms of energy consumption, noise and gas emissions. It is also considered the most cost-effective mode of transport due to low infrastructure and external costs [6]. In terms of safety, inland navigation is at least 50 times safer than road transport [7]. However, some issues that could affect the operation of an inland waterway vessel are limited waterway widths, fluctuations in water level [8] and the effects of the river current [9]. In terms of sustainability, inland waterway transport has an advantage over road transport, e.g. inland waterway transport has lower operational emissions per transported unit. However, this advantage is decreasing since road transport is slowly adapting to environmental trends and implementing alternative options for emission reductions, at least more quickly than the inland waterway sector. In Europe, road transportation is the main mode of land transport with a market share of approximately 76%, while the rest of the market share is divided between railways (18%) and inland waterways (6%) [10]. According to the European Commission, by 2050 the GHG emissions from transport will need to be at least 60% lower than in 1990. Within the European Strategy for Low-Emission Mobility, three priority areas for action are identified: increasing the efficiency of the transport system and encouraging a shift towards transport modes with lower emissions, the use of alternative energy with an emphasis on electrification, and a transition towards zero-emission vehicles [11]. The shift of freight traffic from roads to inland waterways would result in a decrease in road congestion [12], but the negative environmental impact of inland navigation would rise, especially in terms of atmospheric pollution and the impairment of air quality and human health [13] [14].

Since global warming is a major concern and given the existence of many national strategies to reduce transport emissions, which are in accordance with the most relevant climate agreement that promotes a reduction of GHGs, i.e. the Paris Agreement signed in 2016 [15], this paper focuses only on GHG emissions. The contribution to global warming from different GHGs is evaluated with the Global Warming Potential (GWP) which is expressed as the appropriate CO_2 equivalent (CO_2-eq) [16]. In order to quantify the impact of CO_2 emissions, the term Carbon Footprint (CF) is used, denoting the total amount of CO_2 emissions over the product lifetime [17] expressed in tons of CO_2-eq.

The decarbonization of the shipping sector can be achieved through technical and operational measures [18] [19]. One of the technical measures relates to the replacement of conventional fossil fuel with alternative and cleaner fuel with lower carbon content which would reduce the CF of a ship power system [20]. The most frequently used alternative fuel in the shipping sector is Liquefied Natural Gas (LNG), whose application results in lower operating costs and emissions, but the investment costs, the required infrastructure and safety issues are major limitations of its wider use as a marine fuel [21]. Fan et al. [22] investigated its application in inland navigation ships. In their study, environmental and economic assessments indicated that using LNG in a hybrid power system results in lower overall emissions and costs.

Another fossil fuel that has been studied as a potential marine fuel is methanol, whose viability greatly depends on the area of navigation, the fuel price and the capital cost. The performed Life-Cycle Assessment (LCA) indicated that the total CF of fossil methanol is higher than the CF of conventional fuels, due to the larger amount of GHGs released from the LCA stages of fuel production and distribution [23]. A more viable option is to use renewable methanol (biomethanol) which has a lower environmental footprint [24]. However, as indicated by Helgason et al. [25] in their economic assessment of fossil and renewable methanol compared to heavy fuel oil, renewable methanol is expensive, and its application in the shipping sector will only be possible with subsidies. Biofuels, also called green fuels, are produced from renewable sources (waste, vegetable oil or plant biomass). According to environmental comparison of alternative marine fuels, Gilbert et al. [26] highlight biofuels as an ecological option with a CF reduction of 57%-79% compared to conventional marine fuels.

The full electrification of ships is an attractive decarbonization solution. For this type of electrification, a battery is used as energy storage due to its high energy density and low cost compared to other energy storages [27]. This kind of alternative option provides zero-emission shipping, i.e. ship operation without tailpipe emissions. However, an environmental impact analysis of a fully electric ship needs to be performed from the life-cycle point of view, since the emissions released during the electricity production process contribute to atmospheric pollution. The emissions also depend on the electricity mix used in the process [28]. Gagatsi et al. [29] investigated a fully electrified ferry from the point of view of sustainability and cost-effectiveness. Limitations such as battery capacity and sailing distance, but also the high investment costs, still represent obstacles in the wide deployment of battery-powered ships. One of the incentives for shipowners to electrify their ships is the introduction of carbon allowances in the shipping industry. If this happens, shipowners will have to pay a kind of carbon tax for each ton of CO_2 that is released into the atmosphere [30] [31].

The possible application of carbon allowances could also open the way for the use of hydrogen as an alternative marine fuel for use in a fuel cell. However, one of the obstacles to its wider application is hydrogen storage, although it is possible for hydrogen to be produced onboard from hydrogen carriers (i.e. natural gas, methanol, ethanol, ammonia, etc.) [32], [33].

The implementation of alternative fuels in the shipping sector depends on multiple factors, i.e. fuel reserves, available infrastructure, emissions produced, etc. Prussi et al. [34] investigated these factors and found a lack of reliable infrastructure for the use of methanol, hydrogen and electricity as shipping fuel and that the future fuel mix would depend on the potential for reductions in GHGs, technology improvement, and the availability and cost-effectiveness of such alternative solutions. The cost-effectiveness of a power system can be thoroughly investigated by performing a Life-Cycle Cost Assessment (LCCA), which is used in an economic analysis of a ship power system. For example, the comparison of an LCA and LCCA of different alternative fuels for onboard short-sea shipping vessels in a study by Perčić et al. [35] showed that a fully electric ship was the most cost-effective and most environmentally friendly option among those considered. Although they did not analyse electricity as a marine fuel, Nair and Acciaro [36] investigated six fuels for use in the shipping sector and concluded that LNG, besides satisfying environmental regulations in terms of reducing GHGs, represents a profitable investment since the price of the fuel is low.

However, the viability of alternative fuels depends on the fleet type, technical performance, total costs, environmental impact, and exploitation. In addition, the application of alternative fuels should also be investigated for the geographical area of navigation.

Based on the above overview, a gap in the literature is evident: research into alternative fuels to reduce the CF is mainly directed at the long-distance and short-sea shipping sectors, while the possibility of their application in the inland waterway sector has not been adequately investigated. Alternative fuels are particularly important for Croatian inland shipping which consists mainly of outdated vessels with low energy-efficient power systems that need to meet emission reduction targets. Therefore, this paper presents a techno-economic assessment of alternative fuels (electricity, methanol, LNG, hydrogen, ammonia and biodiesel) to reduce the CF of Croatian inland waterways, where three ships are used as test cases. This paper provides a model to calculate the CF of different inland waterway vessels, identifies a set of alternative fuels that can be used in Croatian inland waterways, and, by performing an LCA and LCCA, highlights the most economical and ecological power system configuration.

2. Methodology

2.1. The Croatian inland waterway sector

According to the International Energy Agency, a major contributor to total CO_2 emissions in Croatia is the transport sector with a share of 40% in 2018 [37]. In transport emissions, road transport causes 96.4% of total transport CO_2 emissions, while navigation (which includes both seagoing and inland waterway vessels) generates 2.4% [38], Fig. 1.

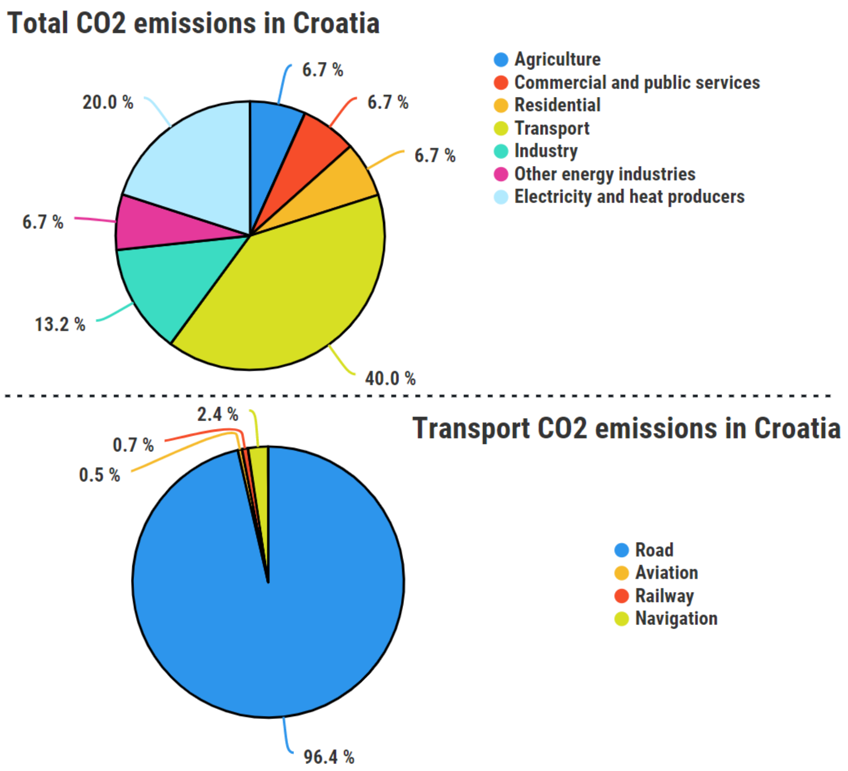

Fig. 1. Croatian total CO_2 emissions [37] and transport CO_2 emissions [38] in 2018

Even though the Croatian inland waterway sector contributes a small share to overall national CO_2 emissions, the national Low-Carbon Development Strategy requires a reduction in GHGs under certain sectoral policies which also apply to the inland waterway sector. Measures for the transport sector include the use of low-carbon fuels, optimizing and increasing the energy efficiency of transportation modes, and promoting the sustainable integrated transportation of passengers and freight, i.e. shifting from road to railway and inland waterway transportation [39].

The Croatian inland waterway network consists of the natural streams of the Danube, Sava, Drava, and Kupa, with a total length of 787.1 km. Even though it is geographically well placed, due to varying navigation conditions, technical obsolescence, and low capacity, Croatia’s inland waterways are underutilized [40]. Some Croatian inland waterway vessels operate on lakes, which mainly belong to protected areas of nature and serve primarily for touristic purposes. The Croatian inland waterway fleet includes several types of ships: dredgers, tugboats (tugs and pushers), passenger ships and cargo ships. All vessels use high-speed four-stroke diesel engines (diesel-mechanical propulsion) [41]. The average age of these ships is around 40 years, which indicates that, in the near future, they will need to be replaced by new ships or at least retrofitted with a new power system. Even though their total emissions are much lower than those generated by marine vessels, their effect on the population in the settlements they pass through is not negligible. Taking into account the relevant national strategy on reducing GHGs, which requires particular measures in the transport sector, the opportunity arises to replace conventional diesel with alternative fuels.

This study divides the Croatian inland waterway fleet into three groups: cargo ships, passenger ships, and working ships (dredgers and tugboats). For each group, a representative has been selected, Fig. 2, and their particulars are presented in Table 1 [41].

Fig. 2. Analysed inland waterway vessels [42], [43], [44]

Table 1 Particulars of the selected ships

	Cargo ship	Passenger ship	Dredger
Length overall, L (m)	75.9	13.2	68.94
Breadth, B (m)	9.0	4.12	9.30
Deadweight, DWT (t)	967	15.72	484.6
Main engine(s) maximum continuous rating, P_{ME} (kW)	855	236	804
Auxiliary engine(s) maximum continuous rating, P_{AE} (kW)	100	-	476
Total power installed, P (kW)	955	236	1,280
Route length, l (km)	223	5	-
Annual number of trips, N_A	20	2,190	-

The representative of cargo ships is the tanker “Opatovac”, which is mostly used to transport oil between two Croatian refineries (Slavonski Brod and Sisak). Besides other factors, the ship speed depends on the direction of navigation (upstream or downstream). The average speed of a cargo ship of this size is 14.4 km/h, with an average main engine load of 75% of the maximum continuous rating [45]. With an average speed of the Sava River of 1 m/s [46], the average duration of the trip is 20.5 h for the upstream and 12.5 h for the downstream trip, respectively. The average load of the auxiliary engines is assumed to be 50% of the maximum continuous rating. The representative of passenger ships is the “Trošenj”, which operates in Krka National Park and usually sails between the Skradin and Skradinski Buk ports. The river speed is negligible. The duration of a one-way trip is 20 minutes, while the average speed is 15 km/h [43]. It is assumed that the ship operates at 70% of the total installed power.

Since the cargo and passenger ships have a particular route on which they sail, the energy consumption, *EC* (kWh/km), per distance travelled is calculated as follows:

$$EC = \frac{P_{ME,ave} \cdot t_{ot}}{l} + \frac{P_{AE,ave} \cdot t_{ot}}{l}, \tag{1}$$

where t_{ot} (h) represents the duration one-way trip. This general equation can be applied both to an upstream and downstream trip. The fuel consumption per distance travelled of a diesel-powered ship, *FC* (kg/km), is calculated by multiplying *EC* with the specific fuel consumption, *SFC* (g/kWh), with the following equation:

$$FC = EC \cdot SFC. \tag{2}$$

For high-speed diesel engines, SFC_D is equal to 215 g/kWh [47]. Assuming a ship lifetime of 20 years, the calculation of the lifetime mileage, *LM* (km), is performed as follows:

$$LM = 20 \cdot N_A \cdot 2 \cdot l. \tag{3}$$

However, equations (2) and (3) cannot be used for the representative of working ships since it does not have a specific route of navigation. The primary task of the dredger "Papuk" is to arrange the riverbed. Using data on the annual fuel consumption of this ship, FC_A (l), which amounts to 63,023 litres and is reported by the shipowner, and with the assumption that the average load of the ship power system is 50% of the rated load, it is possible to approximately determine the time that the dredger spends in operation annually, t_A (h), using the following equation:

$$t_A = \frac{FC_A \cdot \rho}{0.5 \cdot P \cdot SFC_D}, \tag{4}$$

where ρ denotes the fuel density (kg/l) and *P* (kW) denotes the total installed power of the vessel. The annual energy consumption of the dredger, EC_A (kWh), can then be calculated according to the following equation:

$$EC_A = 0.5 \cdot P \cdot t_A. \tag{5}$$

The data for further analysis are calculated and presented in Table 2. For the cargo ship and passenger ship, the data are calculated by equations (1)-(3) and are expressed per km of the travelled trip, while for the ship without a particular route, i.e. the dredger, the annual data are calculated according to equations (4) and (5).

Table 2 Calculated data for the selected ships

Ship with a particular route		
	Cargo ship	Passenger ship

Average duration of a one-way trip, t_{ot} (h)	33	0.33
Average energy consumption, EC (kWh/km)	51.13	11.00
Average fuel consumption, FC_D (kg/km)	11.0	2.36
Lifetime mileage, LM (km)	178,400	438,000
Ship without a particular route		
	Dredger	
Annual operational time, t_A (h)	387	
Average annual energy consumption, EC_A (kWh)	247,695	
Lifetime (years)	20	

The combustion of fuel in marine engines results in tailpipe emissions, which are calculated by multiplying FC with the emission factors, EF (g emission/kg fuel), according to the following equation:

$$TE_i = FC \cdot EF_i\,, \tag{6}$$

where the subscript i refers to any emissions. This is a general equation whose principle is implemented on each considered power-system configuration.

2.2. Life-cycle assessment

2.2.1. General considerations on a life-cycle assessment

The most environmentally friendly alternative ship power system is one with the lowest environmental impact. One of the preferred methods for environmental impact analysis is the LCA which takes into account the emissions released throughout the life cycle of a product, involving several life stages [48].

LCA is performed by means of GREET 2019 software [49], which enables investigation of emissions released from the processes in the Well-to-Pump (WTP) phase (i.e. raw material recovery, production of the fuel and its transportation to the pump) and those released from the processes in the Well-to-Wake (WTW) phase, i.e. the WTP phase and the process of product use, known as the Pump-to-Wake (PTW) phase. PTW emissions refer to the tailpipe emissions. In order to analyse the CF of the entire power system configuration, besides WTW emissions, the emissions released from the manufacturing of its key elements are taken into account. In this study, the total GHGs released during the life-cycle of different ship power systems are expressed in CO_2-eq and calculated as follows:

$$CF = GWP_{CO2} \cdot E_{CO_2} + GWP_{CH_4} \cdot E_{CH_4} + GWP_{N_2O} \cdot E_{N_2O}, \tag{7}$$

where E_{CO2}, E_{CH4} and E_{N2O} refer to the total emissions of CO_2, CH_4 and N_2O released during the ship lifetime. Among the considered marine fuels, diesel, LNG and methanol result in tailpipe emissions. The emission factors for diesel and natural gas are obtained from [50], while the emission factor for methanol is obtained from [51], Table 3.

Table 3 Emission factors

GHG	GWP	Emission factors, *EF* (g/kg fuel)		
		Diesel	LNG	Methanol
CO_2	1	3,206	2,750	1,380
CH_4	25	0.06	51.2	-
N_2O	298	0.15	0.11	-

The system boundary is set on the power system, where the inputs refer to the total energy sources used in the observed life-cycle of a power system configuration, while the output represents the emissions associated with these life-cycle stages. Since the emphasis is on comparing power systems, under consideration here are only emissions related to the power system configurations, and not the ship hull and other ship systems, are considered.

2.2.2. The life-cycle assessment of a diesel-powered vessel

Analysis of the currently used diesel power system configuration represents a baseline to compare different alternative power options for the Croatian inland waterway fleet. It includes emissions released from processes of the WTP phase (crude oil recovery and its transportation to the refinery, refining, and its transportation to the oil pump) and the PTW phase (diesel combustion in an engine), Fig. 3.

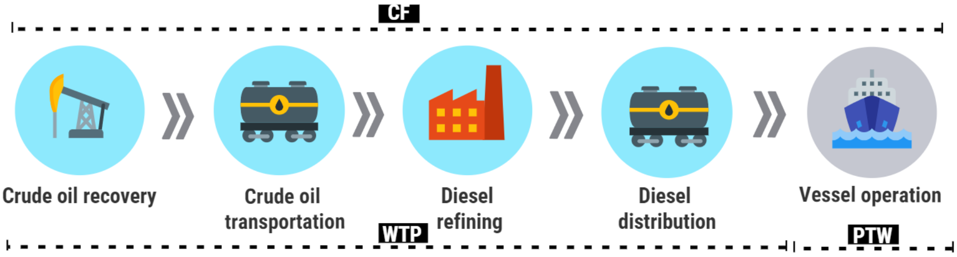

Fig. 3. Processes of the LCA of a diesel-powered vessel

The diesel used by the Croatian shipping sector corresponds to conventional diesel from the GREET 2019 database. Crude oil used for Croatian diesel production is primarily imported from the Middle East since domestic crude oil production is not sufficient for Croatian demand. The process of crude oil transportation involves transport by tank trucks from the exploitation site to the port (500 km), where the crude oil is loaded onto a tanker, which sails for 4,000 km to the Croatian terminal [52]. After the production of diesel, it is transported to the pump by tank trucks. This distance for the cargo ship is 200 km (from Rijeka to Sisak), for the passenger ship it is 300 km (from Rijeka to Šibenik) and for the dredger, it is 450 km (from Rijeka to Osijek).

The emissions released from the PTW phase is calculated according to equation (6). The *EF*s are presented in Table 3.

2.2.3. The life-cycle assessment of an electric-powered vessel

In recent years, fully electric ships have attracted great attention. The power system of these ships consists only of a battery as a power source, which leads to reduced emissions.

Even though it is expensive, a lithium-ion (Li-ion) battery has the highest energy density compared to other types of batteries, and has been widely investigated for shipping purposes [53]. The considered Li-ion battery has energy density values of 0.15-0.22 kWh/kg [54]. The battery capacity, BC (kWh), is defined depending on the operating requirements. It is assumed that for the cargo ship it is sufficient for a one-way trip with an average speed of 14.4 km/h. The battery installed onboard the passenger ship is recharged after a round trip, while the battery used on the dredger has sufficient capacity to provide 8 hours of operation. For safety reasons, the required capacities are increased by 20% and determined by eq. (8) (for the cargo ship and the passenger ship) and eq. (9) (for the dredger):

$$BC = 1.2 \cdot EC \cdot (2) \cdot l, \tag{8}$$

$$BC = \frac{1.2 \cdot EC_A}{t_A} \cdot 8. \tag{9}$$

The LCA of an electric-powered ship includes electricity generation and the process of battery manufacturing, Fig. 4. During its operation, the vessel does not release exhaust gases. Hence, it produces zero PTW emissions.

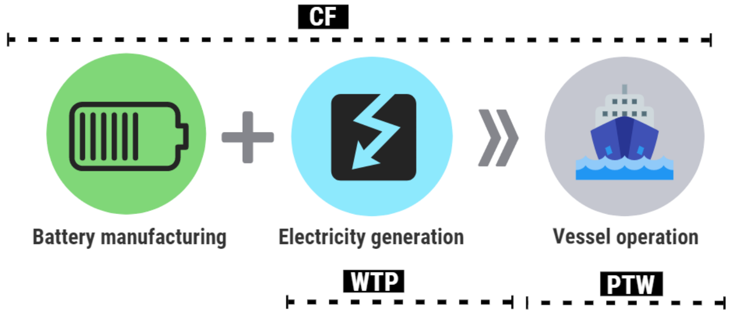

Fig. 4. Processes of the LCA of an electric-powered vessel

The WTP phase of electricity refers to the process of electricity generation. The structure of the Croatian electricity mix is shown in Fig. 5 [55].

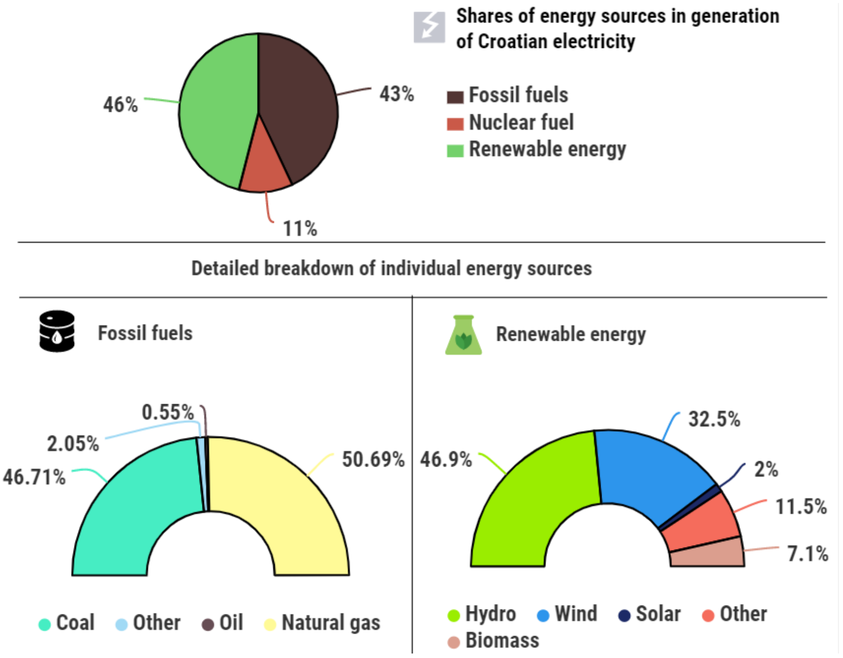

Fig. 5. Croatian electricity mix in 2018 [55]

The environmental impact of a battery is assessed taking into account the manufacturing process using data from the software database. The only required input is the battery weight which is calculated by dividing its capacity by its specific energy (0.22 kWh/kg). Replacement of the battery after ten years is also assumed.

2.2.4. The life-cycle assessment of a methanol-powered vessel

The second option to replace diesel fuel is methanol: a toxic, corrosive, but sulphur-free and biodegradable fuel. The main raw material for its production is natural gas and, due to the low carbon content, it has been attracting wide attention. Its similarity to marine fuels (due to its liquid state) allows for methanol to be used in the current diesel infrastructure with only minor modifications [56]. It can be easily used in the commercially available MAN dual-fuel engine, which uses a small amount of pilot fuel to initiate combustion [57]. In this paper, the considered vessels operate only in a dual-fuel mode with 95% of methanol and 5% of diesel (pilot fuel). The power output of the dual-fuel engine needs to be sufficient to cover the total installed power. Specific fuel consumptions refer to a load of 75% [58], Table 4.

Table 4 Dual-fuel engine for the considered vessels

	Cargo	Passenger	Dredger
Dual-fuel engine type	MAN G50ME-C9.6-LGIM		
Engine power (kW)	955	236	1,280
Specific consumption of methanol (SFC_M), g/kWh	327.2		
Specific consumption of pilot fuel (SFC_{P-M}), g/kWh	10.1		

The fuel consumptions in a dual-fuel engine can be calculated as follows:

$$FC_f = x_f \cdot EC \cdot SFC_f, \tag{10}$$

$$FC_{P-f} = x_{P-f} \cdot EC \cdot SFC_{P-f}, \tag{11}$$

where FC_f and FC_{P-f} refer to the consumption of the main fuel and pilot fuel, while x_f and x_{P-f} represent the proportions of the main fuel and pilot fuel in a dual-fuel engine, respectively. This general equation can be applied to each power system configuration which includes a dual-fuel engine.

The processes included in the LCA of a methanol-powered vessel refer to the WTP phase of methanol, the WTP phase of diesel from section 2.2.2, and combustion in a dual-fuel engine in the PTW phase, Fig. 6.

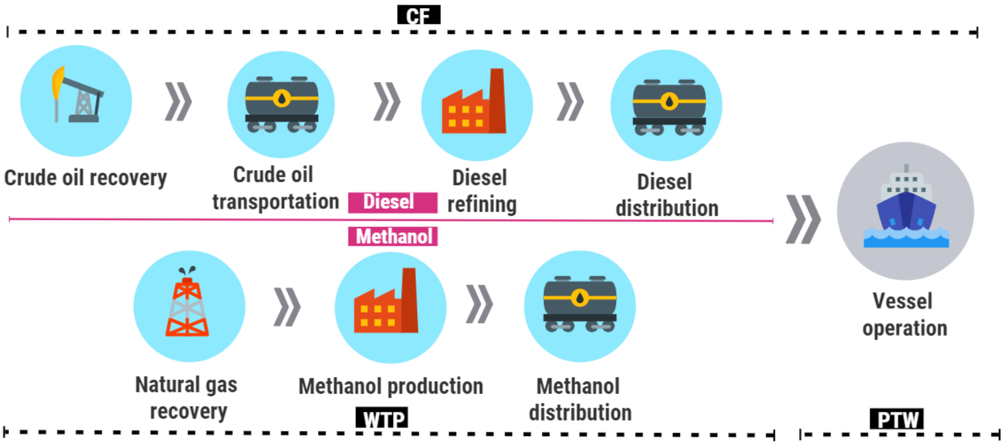

Fig. 6. Processes of the LCA of a methanol-powered vessel

The WTP phase of methanol includes the processes of natural gas recovery, the production of methanol and its transportation to the pump. It is assumed that methanol is made from natural gas by steam reforming and is produced in the Egyptian methanol plant from which it is transported via tanker to Croatia (3,000 km) [59]. Once the methanol is shipped to Croatia, it is transported via tank truck to pumps.

In the dual-fuel engine, both methanol and diesel as a pilot fuel are combusted and the released emissions are calculated according to equation (6). The *EF*s are presented in Table 3.

2.2.5. The life-cycle assessment of an LNG-powered vessel

As an affordable, non-toxic and non-corrosive fuel with lower carbon content than diesel, natural gas is competitive on the energy market for use as an alternative shipping fuel [60]. As in the case of a methanol-powered vessel, natural gas is usually used in a dual-fuel diesel engine that provides high efficiency and offers a smooth switch between one fuel and the other during ship operation without loss of power or speed [61]. Natural gas is originally in gaseous form. To make the handling process easier, natural gas is liquefied by cooling it at -163 °C. In this way, LNG has 600 times less volume than in its gaseous state [62]. This study investigates the use of LNG in the Croatian inland waterway sector. It is used in a dual-fuel engine with diesel as a pilot fuel in a proportion of 1%. For a load of 75%, the specific consumption of LNG (SFC_{LNG}) is 154.4 g/kWh, while the specific consumption of pilot fuel ($SFC_{P\text{-}LNG}$) is 1.8 g/kWh [63]. The fuel consumption of LNG (FC_{LNG}) and pilot fuel ($FC_{P\text{-}LNG}$) is calculated according to equations (10) and (11).

The LCA of an LNG-powered vessel includes the processes related to the diesel part of the configuration (from section 2.2.2), those related to LNG, and the ship operation during which PTW emissions are released, Fig. 7.

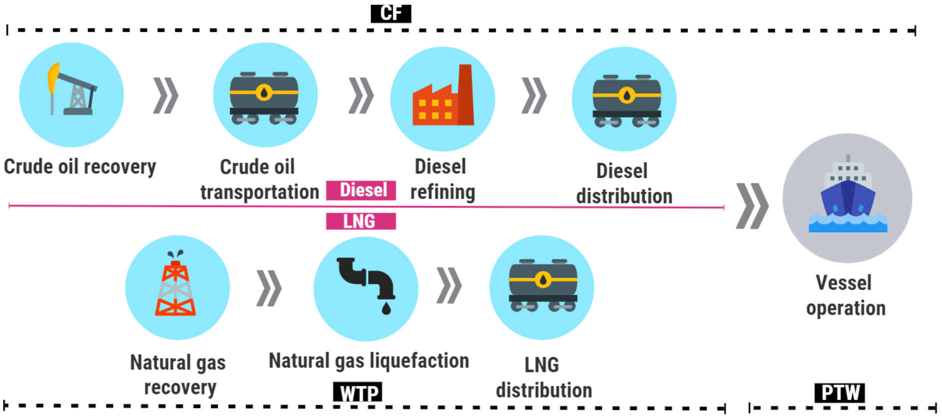

Fig. 7. Processes of the LCA of an LNG-powered vessel

The WTP phase encompasses the processes of natural gas recovery, its liquefaction and transportation. It is assumed that LNG is transported from Qatar via LNG carriers that transport it around 7,000 km to Croatia. Further transportation is made by tank truck for distances that correspond to the distances for diesel transportation (section 2.2.2).

In the dual-fuel engine, both LNG and diesel as a pilot fuel are combusted and the released emissions are calculated according to equation (6). The *EF*s are presented in Table 3.

2.2.6. The life-cycle assessment of a hydrogen-powered vessel

Hydrogen is an abundant and non-toxic fuel that is rarely found in pure form. It is usually produced from natural gas, but can also be obtained from biomass and by electrolysis [64]. Hydrogen is usually used in a fuel cell, which enables direct conversion of the chemical energy of fuel into electric energy via electrochemical reactions. Although the literature regularly considers the application of fuel cells only as an auxiliary power source, here, for comparative purposes, its use for ship propulsion is considered. Once the hydrogen is supplied to the ship, it is fed to a Proton Exchange Membrane (PEM) fuel cell. The characteristics of this type of fuel cell are its low operating temperature (65-85°C) and, given its intolerance to impurities, its requirement for pure hydrogen as fuel [65]. With an efficiency of 48% (η_{FC}) [66], the selected PEM fuel cells have power equal to the total installed power of the existing vessels. Considering the *EC* of a vessel, the net calorific value of hydrogen (NCV_H) which is equal to 33.3 kWh/kg, and η_{FC}, the hydrogen consumption, (FC_H) can be calculated:

$$FC_H = \frac{EC}{\eta_{FC} \cdot NCV_H}. \tag{12}$$

The LCA of a hydrogen-powered vessel includes the manufacturing process of a fuel cell, natural gas recovery, hydrogen production and its liquefaction, its distribution by tank trucks, and vessel operation during which there are no tailpipe emissions, Fig. 8.

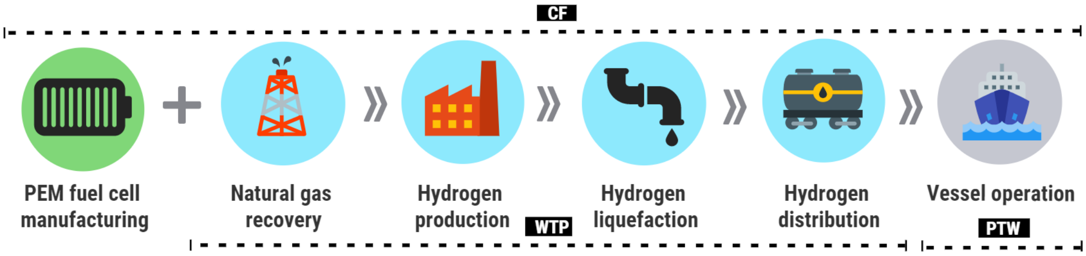

Fig. 8. Processes of the LCA of a hydrogen-powered vessel

The considered hydrogen is produced from natural gas in Western Europe and, after its production and liquefaction, it is transported to Croatia by tank trucks (distances: cargo ship: 1,200 km; passenger ship: 1,300 km; dredger: 1,450 km). The weights of materials used in the PEM fuel cell are taken from [67] and further used as an input for GREET 2019. Replacement of the fuel cells after 10 years is also assumed.

2.2.7. The life-cycle of an ammonia-powered vessel

Ammonia is a hydrogen-rich fuel. It is mostly produced through the Haber-Bosch process, where nitrogen from the air and hydrogen are combined at high temperature and pressure. A well-established infrastructure and the lack of carbon content in ammonia make it a promising option for the shipping sector [68] [69].

In this paper, ammonia is considered as a hydrogen carrier. The ammonia needs to be processed through a cracker, where the decomposition of ammonia into hydrogen and nitrogen occurs, and then the hydrogen is passed through a purifier to ensure that only purified hydrogen enters into the fuel cell [70]. While the particulars for the PEM fuel cell correspond to those in section 2.2.6, the fuel consumption of ammonia (FC_{AM}) is calculated as follows:

$$FC_{AM} = \frac{EC}{\eta_{CR} \cdot \eta_{PR} \cdot \eta_{FC} \cdot NCV_{AM}}. \tag{13}$$

where η_{CR} and η_{PR} refer to the efficiency cracker (80%) and purifier (90%) [70], while the NCV_{AM} refers to the net calorific value of ammonia which is equal to 5.17 kWh/kg [64].

The LCA of an ammonia-powered vessel includes the manufacturing process of a fuel cell, natural gas recovery, ammonia production and its distribution by tank trucks, Fig. 9. There are no tailpipe emissions while the ship is operating.

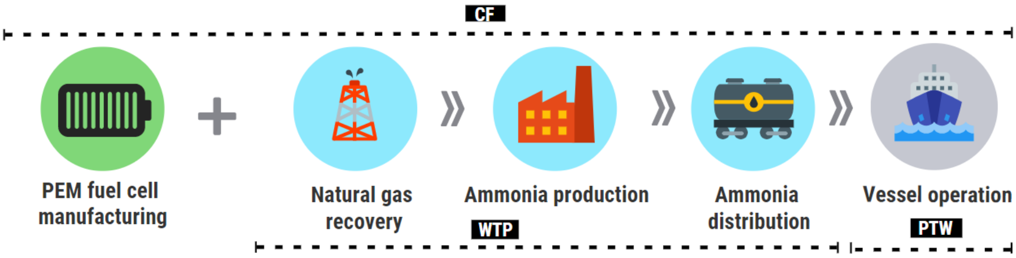

Fig. 9. Processes of the LCA of an ammonia-powered vessel

Ammonia is considered to be produced on the same site as the hydrogen, where it is distributed in the same manner as the hydrogen. The environmental impact of a fuel cell is the same as the calculated for the hydrogen-powered ship.

2.2.8. The life-cycle assessment of a B20-powered vessel

In recent years, biofuels have also been attracting interest. The most commonly produced biofuel is biodiesel whose feedstock can be classified into four main groups: edible vegetable oil (sunflower, soybean, rapeseed etc), non-edible vegetable oil (algae, cottonseed, jojoba etc.), recycled and waste oil, and animal fat [71]. Biodiesel is usually used as a blend with fossil fuels, and is designated as BXX, where XX indicates the biodiesel percentage in a blend. The blend usually used as a transportation fuel contains a low share of biodiesel [72].

This study considers the soybean biodiesel-diesel blend B20 in which Croatian diesel is used (section 2.2.2), while the soybean biodiesel is imported from the Veneto region of Italy [73]. The WTP phase of the biodiesel consists of several processes: soybean farming and soy oil extraction, soy oil transportation by tank trucks (50 km) to the transesterification plant. The produced biodiesel is then transported to a refuelling station where it is assumed that the biodiesel and diesel are mixed into a B20 blend. Transportation distances are different for each considered vessel: 450 km (cargo ship), 550 km (passenger ship) and 700 km (dredger). The performed LCA of a B20-powered vessel includes the processes presented in Fig. 10.

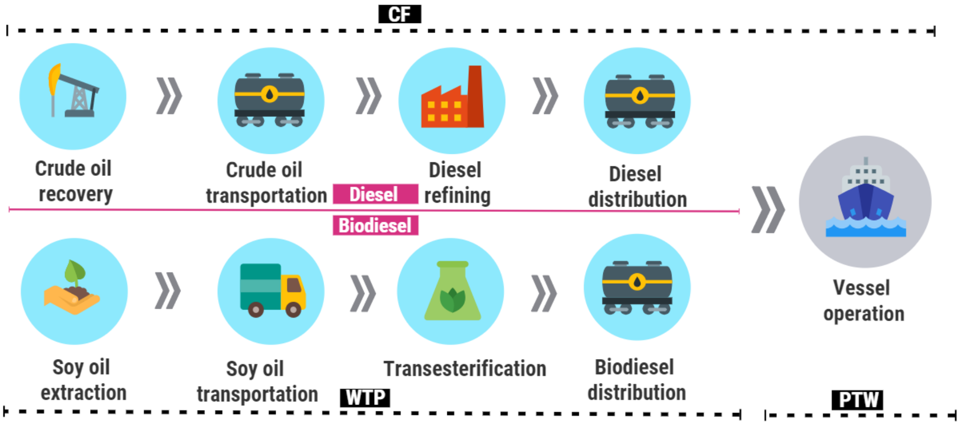

Fig. 10. Processes of the LCA of a B20-powered vessel

Given the general opinion that biofuels are considered carbon-neutral fuels, biodiesel tailpipe CO_2 emissions are not included in total life-cycle emissions, while CH_4 and N_2O emissions are considered negligible [74]. The PTW emissions released by a B20-powered vessel consist of the emissions related only to the diesel and are calculated according to equation (6). The *EF*s are presented in Table 3.

2.3. Life-cycle cost assessment

2.3.1. General considerations on life-cycle cost assessment

LCCA considers the total costs of a power system configuration during the ship lifetime. These life-cycle costs refer to the investment cost and exploitation cost.

The investment cost represents the capital cost of the power system, the maintenance cost refers to the maintenance and equipment replacement cost, while the fuel cost relates to the life-cycle cost of a fuel that is used in the power system. The carbon credit cost refers to the cost of carbon allowance, which represents the right to emit 1 ton of CO_2 [30]. Even though the inland shipping sector has not yet implemented carbon credit, this paper investigates its implementation through different scenarios, as performed by Trivyza et al. [75]. The considered scenarios refer to the non-taxation (NT) scenario and three carbon credit scenarios: the Current Policies (CP) scenario considers the current policies implemented in the energy sector, without additional changes in the future; the Stated Policies (SP) scenario relates to current policies and today's policy targets; and the Sustainable Development (SD) scenario refers to the strategic pathway to meet global climate, air quality and energy access goals. The forecast carbon allowance, CA (€/t CO_2) and the values for 2030 and 2040 in the European Union for each scenario are obtained from [76] and interpolated to obtain relevant trends. For 2020, the CA value is zero, since carbon credit has not yet been implemented, Fig. 11.

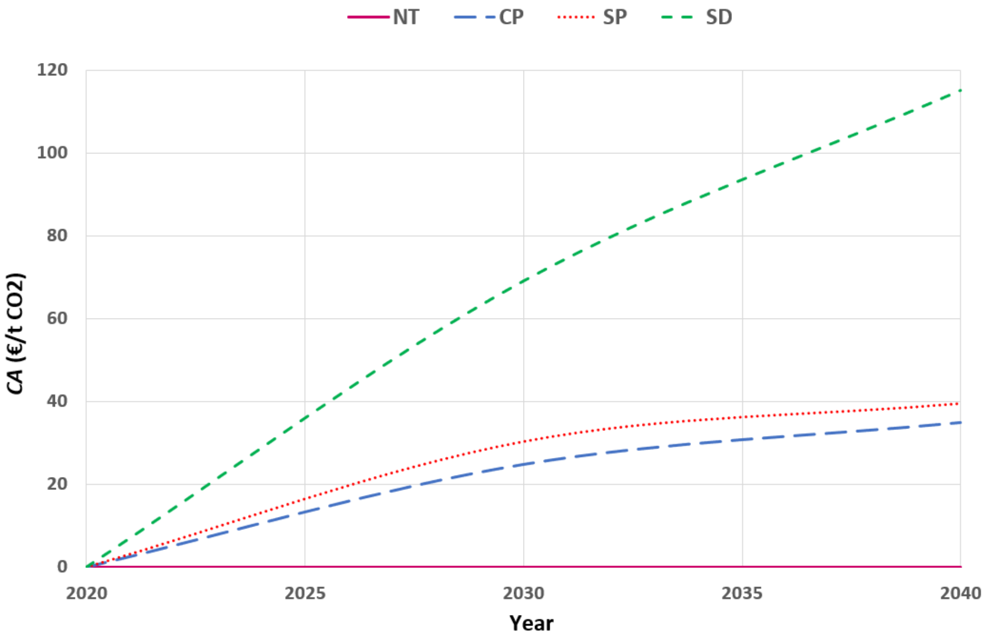

Fig. 11. Carbon allowance scenarios according to [76]; NT - non-taxation scenario, CP - current policies scenario, SP - stated policies scenario, SD - sustainable development scenario

The carbon credit cost is illustrated only for ship power systems that release PTW emissions. The life-cycle carbon credit cost, *LCCCC* (€), for different scenarios yields:

$$LCCCC = \sum_{n=1}^{20} PTW_{A,n} \cdot CA_n, \tag{14}$$

where *n* refers to one year of the ship lifetime, $PTW_{A,n}$ denotes annual tailpipe emissions in t CO_2-eq, while CA_n refers to the carbon allowance for year *n*.

A proper cost comparison of different power system configurations can be achieved by reducing their total costs to the Net Present Value (*NPV*), a measure that discounts the future costs to the present value. The *NPV* of each power system is calculated as follows:

$$NPV = IC + \sum_{n=1}^{20} \frac{AC_n}{(1+r)^n}, \tag{15}$$

where *IC* (€) refers to the investment cost, AC_n (€) represents all annual costs in a year n (including the fuel cost, maintenance cost and carbon credit cost), *r* refers to the discount rate and *n* is the number of years, i.e. the lifetime of a ship.

2.3.2. The life-cycle cost assessment of a diesel-powered vessel

Since most Croatian inland waterway vessels are powered by outdated diesel engines, the purchase of a new diesel power system configuration is investigated. The investment cost of a diesel engine is calculated by multiplying the total installed power with the assumed conversion factor of 250 €/kW. The maintenance conversion factor of this power system is obtained from [77] and is 0.014 €/kWh. The life-cycle maintenance cost of the diesel power system of the cargo and the passenger ship is calculated by multiplying the conversion factor by EC and LM, while for the dredger the conversion factor is multiplied by FC_A and the lifetime of 20 years.

The life-cycle fuel cost ($LCFC_f$) of the cargo ship and the passenger ship is obtained by equation (16), while for the dredger these total fuel costs can be calculated using equation (17), where subscript f refers to any fuel used in the power system:

$$LCFC_f = LM \cdot FC_f \cdot PR_f, \tag{16}$$

$$LCFC_f = 20 \cdot FC_{A,f} \cdot PR_f. \tag{17}$$

The diesel price used in this assessment amounts to 0.78 €/kg [78]. The carbon credit cost is calculated according to equation (14).

2.3.3. The life-cycle cost assessment of an electric-powered vessel

A major obstacle in the electrification of the shipping sector is the high investment cost of an electric-powered vessel (IC_E). In this paper, it is calculated according to the equation below, where it is assumed that 45% of IC_E refers to the battery price, while the rest represents installation, electric engine and additional equipment costs [79]:

$$IC_E = \frac{BC \cdot PR_B}{0.45}, \tag{18}$$

where PR_B refers to the battery price which is assumed to be 200 €/kWh [80]. The maintenance cost relates only to the replacement of the battery after 10 years. According to Tsiropoulos et al. [80], the forecast Li-ion battery price for 2030 is 169 €/kWh.

The electricity price for a Croatian medium-sized enterprise is 0.078 €/kWh [78]. The life-cycle fuel cost of an electric-powered vessel can be calculated according to equations (16) and (17), where, instead of fuel consumption, energy consumption is considered.

2.3.4. The life-cycle cost assessment of a methanol-powered vessel

Conversion from a diesel power system configuration to a methanol power system configuration results in a cost of 750 €/kW for a new-build system which considers the purchase of a new engine and associated equipment [51]. It is assumed that the life-cycle maintenance cost of a methanol-powered ship is equal to the life-cycle maintenance cost of a diesel-powered ship. The life-cycle fuel cost of a methanol-powered vessel can be calculated with equations (16) and (17), where the *FC* and prices of both pilot fuel and methanol are considered. The methanol price amounts to 0.325 €/kg, which is calculated by increasing the price set by the producer, i.e. 0.26 €/kg with Croatian VAT of 25% [59]. The carbon credit costs are calculated according to eq. (14).

2.3.5. The life-cycle cost assessment of an LNG-powered vessel

The investment cost of a new-build LNG system is calculated by multiplying the conversion rate (which includes the engine and all additional equipment costs) of 1,160 €/kW [51] by the engine power, Table 4. The life-cycle maintenance cost is calculated as for the diesel-powered vessel, where the conversion factor is equal to 0.015 € [77].

The price for 1 kg of LNG in Europe varies from 0.95 € to 1.1 €. For this assessment, the LNG price is assumed to be 1.1 €/kg. The life-cycle fuel cost of a methanol-powered vessel can be calculated with equations (16) and (17), where the *FC* and prices of both pilot fuel and LNG are considered. The carbon credit for each power system configuration is calculated according to eq. (14).

2.3.6. The life-cycle cost assessment of a hydrogen-powered vessel

The investment cost of a hydrogen-powered vessel includes a PEM fuel cell (368 €/kW) [81], which is increased by 20% in order to take into account additionally required equipment, while the hydrogen storage cost is calculated by multiplying the amount of hydrogen required for ship operation by the NCV_H and liquid hydrogen storage price of 5 €/kWh. The required mass of hydrogen is increased by 20% for safety reasons [82]. The life-cycle maintenance cost refers only to the replacement once in the ship's lifetime of the fuel cell and is equal to its capital cost. The life-cycle fuel cost of a hydrogen-powered vessel can be calculated with equations (16) and (17), where the hydrogen price lies in the range of 5.35-9.5 €/kg [83] [84]. For this assessment, the upper limit of the range is used in the assessment.

2.3.7. The life-cycle cost assessment of an ammonia-powered vessel

By considering the required cracker and purifier, the investment cost of an ammonia-powered vessel is calculated by increasing the PEM fuel cell cost by 30%. The life-cycle maintenance cost refers only to the replacement of the fuel cell once in the ship's lifetime and is equal to its capital cost.

The life-cycle fuel cost of an ammonia-powered vessel can be calculated with equations (16) and (17), where the price of ammonia is 0.7 €/kg [70].

2.3.8. The life-cycle cost assessment of a B20-powered vessel

The investment and the maintenance costs of a B20-powered vessel are equal to the investment and maintenance costs of a diesel-powered vessel. The price of pure biodiesel is assumed to be the same as the price of Croatian diesel (1.48 €/kg) [78]. The life-cycle fuel cost of a B20-powered vessel can be calculated with equations (16) and (17), where the FC and the prices of both biodiesel and diesel are considered.

The carbon credit for each power system configuration is calculated according to eq. (14).

2.4. Limitations and approximations

The limitations and approximations in this paper are listed as follows:

- The system boundary is fixed to the ship power systems, where the emissions and costs are related only to the ship power system, while the other units of the ship, i.e. the hull, additional equipment, crew, etc., are not taken into account given that they are considered to remain the same while the power is brought to the propeller. However, this approach is sufficiently accurate to identify technical solutions to reduce emissions generated by the power system. This is important since relevant regulations recognize the ship as a separate unit and evaluate its particular contribution.

- Since the cargo ship speed is approximated according to the ships of the same type and size (according to [45]) and has an impact on both emissions and costs, a relevant sensitivity study is included in the discussion section.
- Idealization of the fuel distribution processes and the transportation of the raw material to the production facility are one of the approximations in the paper. However, stationary processes generate most of the WTP emissions, and, therefore, a change in the distribution and transportation pathways would not have a major impact on the WTP emissions.
- Stationary processes of fuels within the WTP phase for all fuels are taken from the GREET 2019 database. For some fuels like biodiesel, this may cause some minor inaccuracies, bearing in mind the fact that this fuel is mainly produced from different feedstocks in the United States (soy and palm) and Europe (rapeseed, sunflower and palm). However, for biodiesel, the contribution of the stationary process to the total emission amounts is relatively small (particularly for biodiesel-diesel blend B20), and this assumption has practically no influence on the overall findings.
- The assumption about the investment cost of additional equipment for fuel cell system does not have a major influence on the final LCCA results since the investment cost of such a power system is relatively minor compared to other costs of that power system.
- An increase in fuel prices in the future is not considered, and therefore the cost assessments follow the business-as-usual scenario. The variability of hydrogen costs is presented in the sensitivity analysis within the discussion section.
- Other limitations of the paper may be that the cost assessment is performed without considering interest rates and that the study focuses only on the ship power system without considering the costs of the ship crew, port fees and other expenses.

3. Results

The LCA and LCCA results of the investigated vessels are presented in Fig. 12 where D denotes diesel, E denotes electricity, M refers to methanol, H refers to hydrogen, AM refers to ammonia, while BD refers to the biodiesel-diesel blend B20. In the LCCA, the SD scenario as a carbon credit implementation scenario is considered.

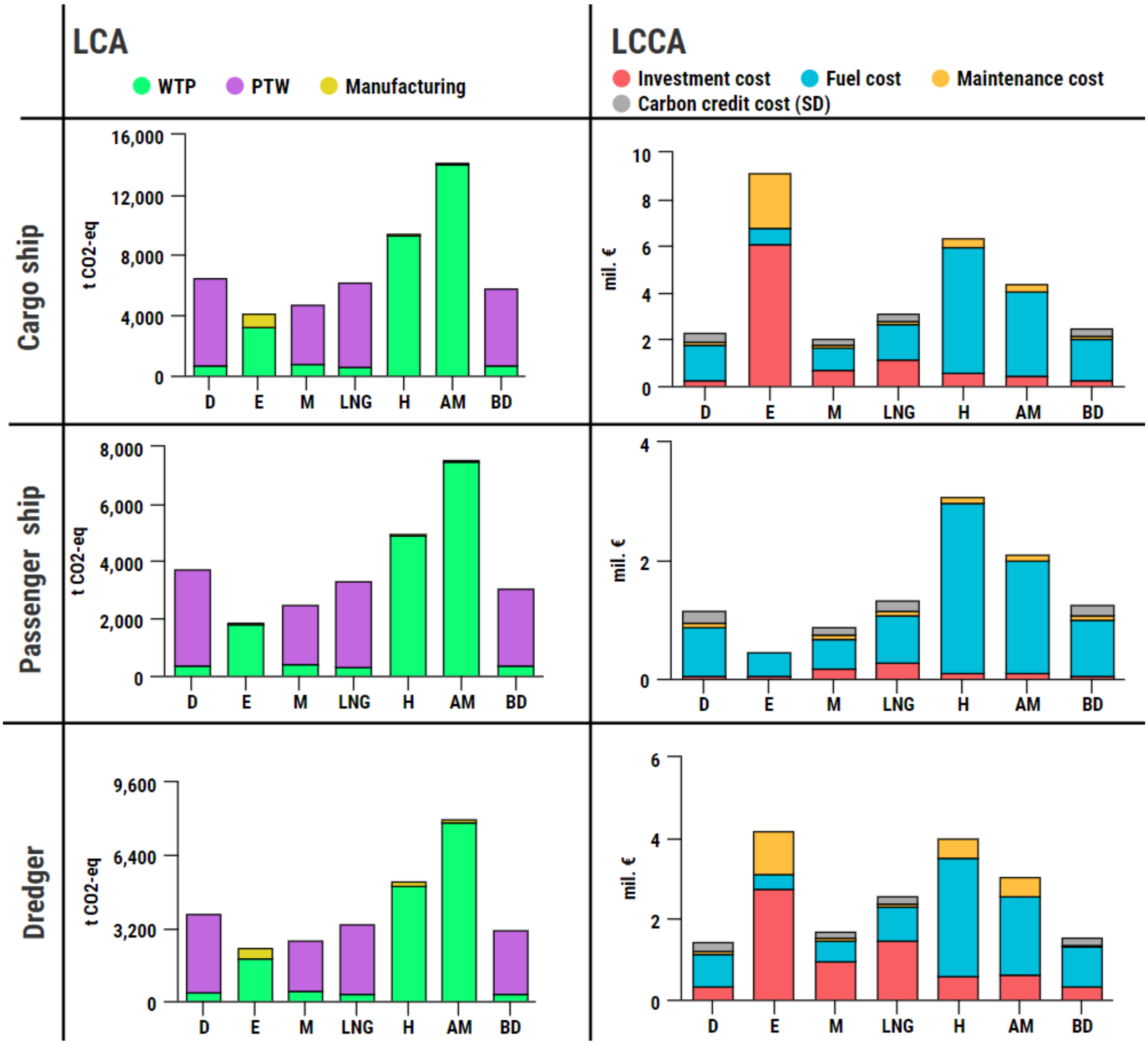

Fig. 12. A comparison of the LCA and LCCA of alternative fuels; D - diesel, E - electricity, M - methanol, LNG - liquefied natural gas, H - hydrogen, AM - ammonia, BD - biodiesel-diesel blend B20

An insight into the impact of individual costs on the total *NPV* of each power system, with an assumed discount rate of 5%, is performed and presented in Fig. 13. The analysis is performed using the example of the cargo ship.

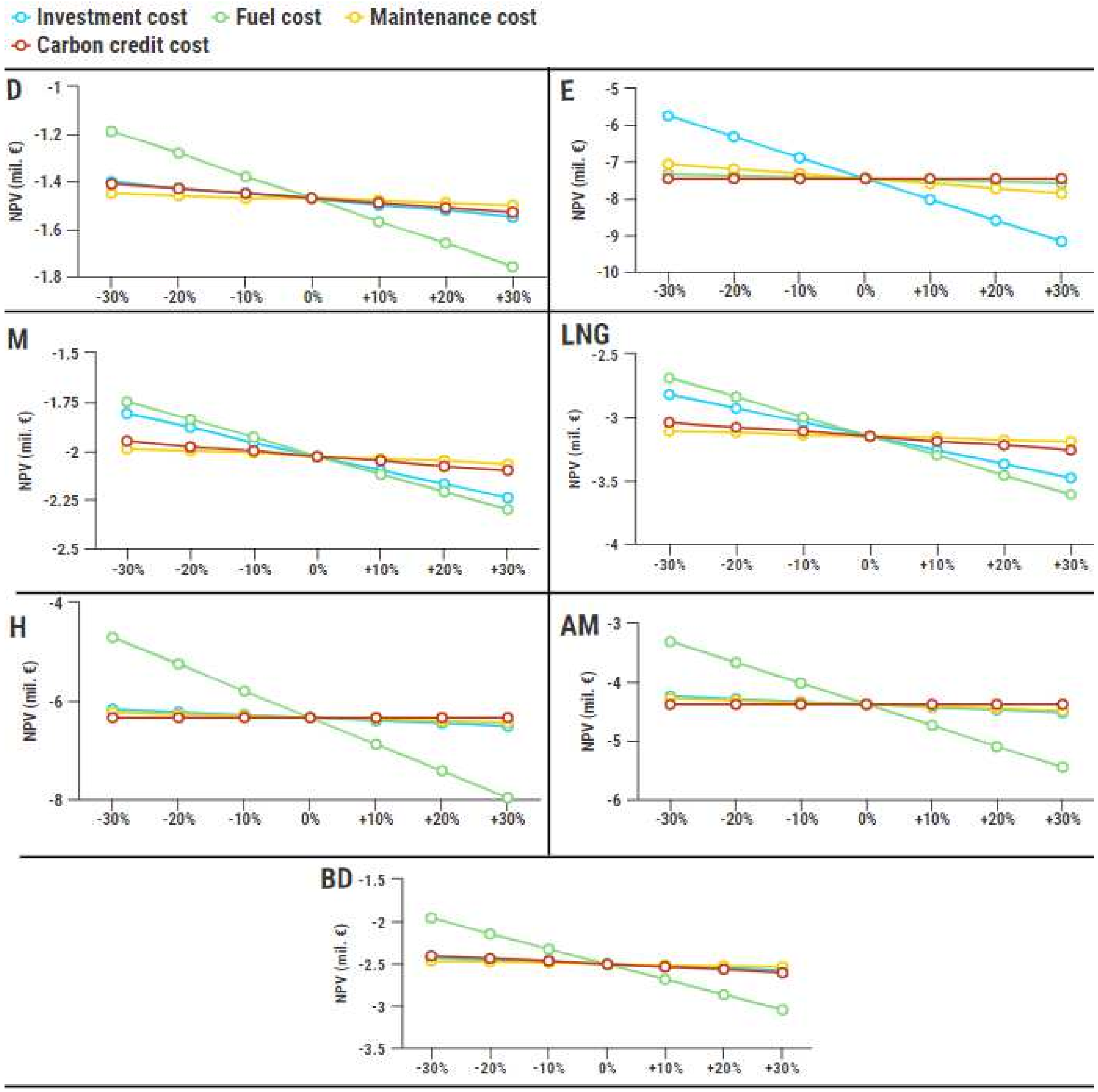

Fig. 13. Impact of individual costs on the *NPV* for different power systems; D - diesel, E - electricity, M - methanol, LNG - liquefied natural gas, H - hydrogen, AM - ammonia, BD - biodiesel-diesel blend B20

The obtained results are extensively discussed in the following section.

4. Discussion

A comparison of the LCA results shows that the most environmentally friendly decarbonisation solution, for each considered vessel, is an electric-powered vessel that involves replacing the diesel engine with a Li-ion battery. The application of this power system results in a CF reduction of 36% for the cargo ship, 51% for the passenger ship and 40% for the dredger. The great difference between these percentages is mainly related to the required battery capacity as well as to the lifetime energy consumption of each vessel. This power system configuration does not release exhaust gas during operation, and its CF is constituted by the emissions related only to electricity generation and the manufacturing of the battery. The electricity mix used for electricity generation has a great effect on the WTP emissions, and an increased share of Renewable Energy Sources (RESs) in the mix would reduce these emissions. Three different scenarios with different electricity mixes are observed to describe the effect of the electricity power origin on the total WTP emissions of an electric-powered ship, where the passenger ship is taken as a test case, Fig. 14.

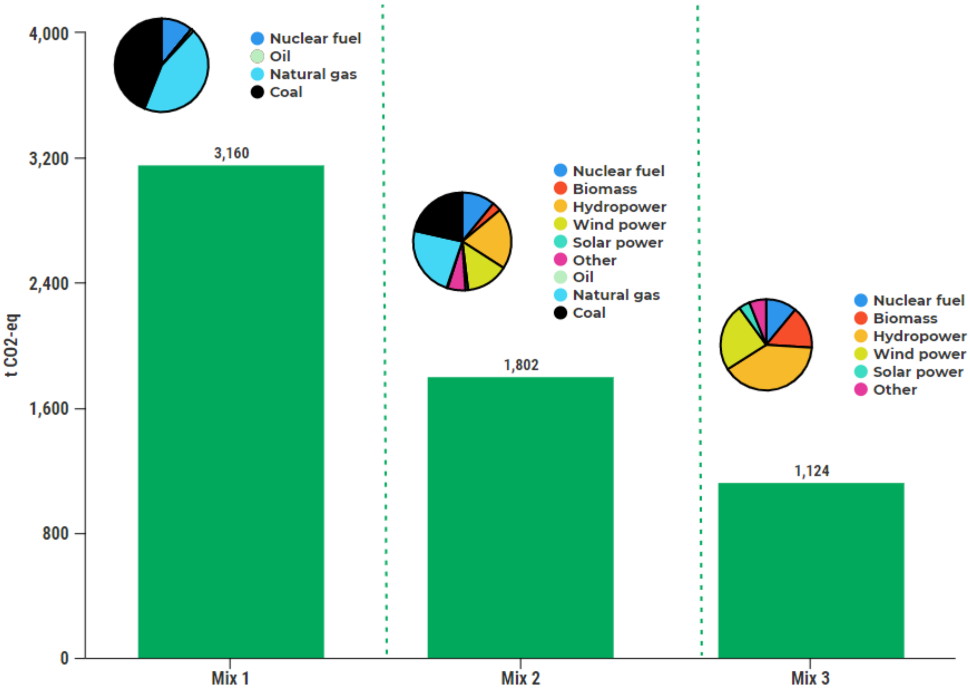

Fig. 14. The WTP emissions of an electric-powered passenger ship with different electricity mixes

Mix 2 refers to the Croatian mix used in this paper, Mix 1 is a mix of only fossil energy sources and nuclear energy, while Mix 3 represents an electricity mix with only RESs and nuclear energy. It is evident that Mix 3 results in the lowest total WTP emissions and that by increasing the share of RESs in the Croatian electricity mix, the emissions related to electrification would be lower.

Other alternative fuels that can be used in Croatian inland waterways and which have a lower CF than a diesel-powered vessel are methanol, LNG and B20. Methanol is indicated as the second most environmentally friendly option, and its application would result in a CF reduction of 28% (for the cargo ship), 33% (for the passenger ship) and 30% (for the dredger). The reason for this is the lower emission factors, Table 3. The ammonia-powered vessel is the ship power system with the highest CF among those investigated in this study. The main reason is the use of fossil ammonia (produced from natural gas) which is required in great amounts due to losses in the cracker and purifier. Applying other fuel cells which tolerate impurities, hence allowing fuel to enter the fuel cell without a precleaning process, would lower the WTP emissions of the ammonia-powered vessel. Using hydrogen onboard inland waterway vessels would result in high emissions. Even though one of the benefits of this configuration is that there are no tailpipe emissions, the WTP emissions are not negligible, and they constitute most of the CF.

The performed LCCAs resulted in revealing the most cost-effective power option for each ship. This option for the cargo ship is a methanol-power system, while for the dredger the power option with the lowest total costs is diesel power. However, following environmental trends, diesel-powered vessels will need to be replaced with some power system that has a lower CF compared to the currently used power system and which does not involve high total costs. This kind of option is hence a methanol-powered system. Due to the required battery capacity, and consequently the high investment cost of battery and hydrogen, an electric-powered vessel and a hydrogen-powered vessel are rather expensive for use in cargo ships and dredgers engaged in the Croatian inland waterway fleet.

Bearing in mind that the target hydrogen price is below 3 €/kg [85], four different hydrogen prices are observed in the analysis where the passenger ship is taken as a test case, Fig. 15.

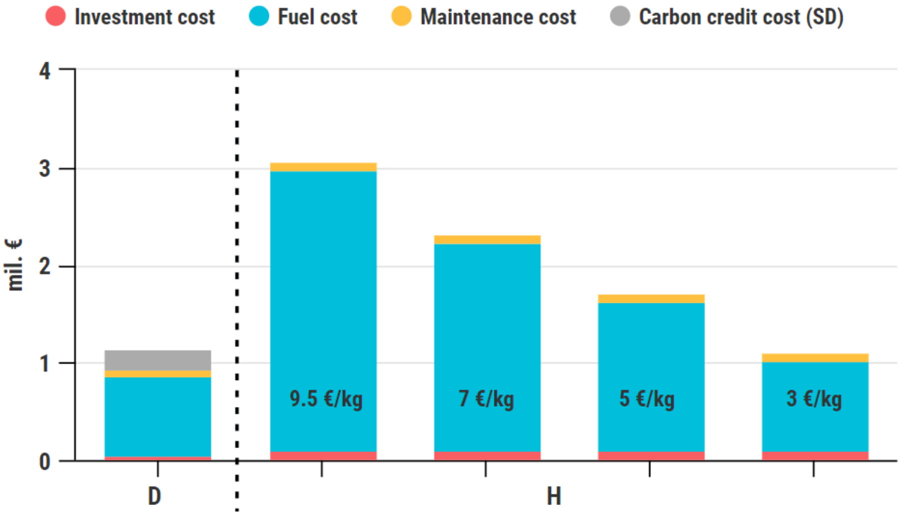

Fig. 15. Sensitivity analysis of the hydrogen price on the total costs of the hydrogen-powered passenger vessel; D - diesel, H - hydrogen

The analysis shows that a hydrogen-powered vessel has lower costs than a diesel-powered vessel only when the price of hydrogen drops to 3 €/kg. Then, the cost of such a configuration is 4% less than the cost of an existing passenger ship. By using green hydrogen, i.e. hydrogen produced from RESs, and with a target fuel price, hydrogen will be a very good alternative solution for replacing the diesel power system configuration. However, in this paper, the LCCA results for the passenger ship indicate an electric-powered vessel as the most economical solution. The total life-cycle costs of this configuration are around 60% lower than the costs of the current power system installed on the considered vessels. It needs to be emphasized that the passenger ship has the longest operating time among the considered vessels, and it requires autonomy of approximately one hour. The calculated payback period is within 3 years.

For the considered cargo ship, a sensitivity analysis of the effect of speed on the life-cycle emissions and the life-cycle costs of different power system configurations was performed. The speed varies by ± 30%, with a step increment of 10%. With a change of speed, the average power also changes. Since ship power is roughly proportional to the cube of its speed, the average ship power for different speeds is calculated. As presented in Fig. 16, the increase and decrease of speed have a great effect on total emissions. For example, a 20% increase in speed raises emissions by 44%, while a 10% decrease emissions by 19%.

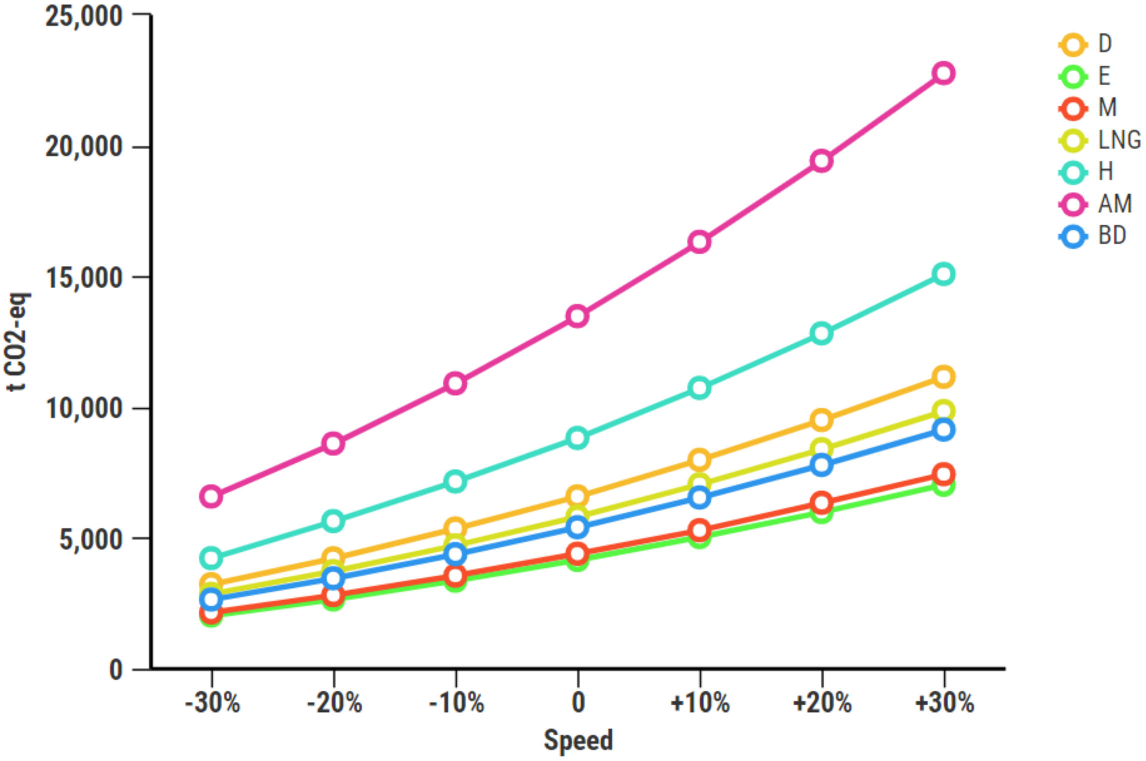

Fig. 16. Impact of ship speed on the life-cycle emissions of different power systems; D - diesel, E - electricity, M - methanol, LNG - liquefied natural gas, H - hydrogen, AM - ammonia, BD - biodiesel-diesel blend B20

The impact of speed variations on the *NPV* of an individual ship power system is presented in Fig. 17, where an assumed discount rate is also set at 5%.

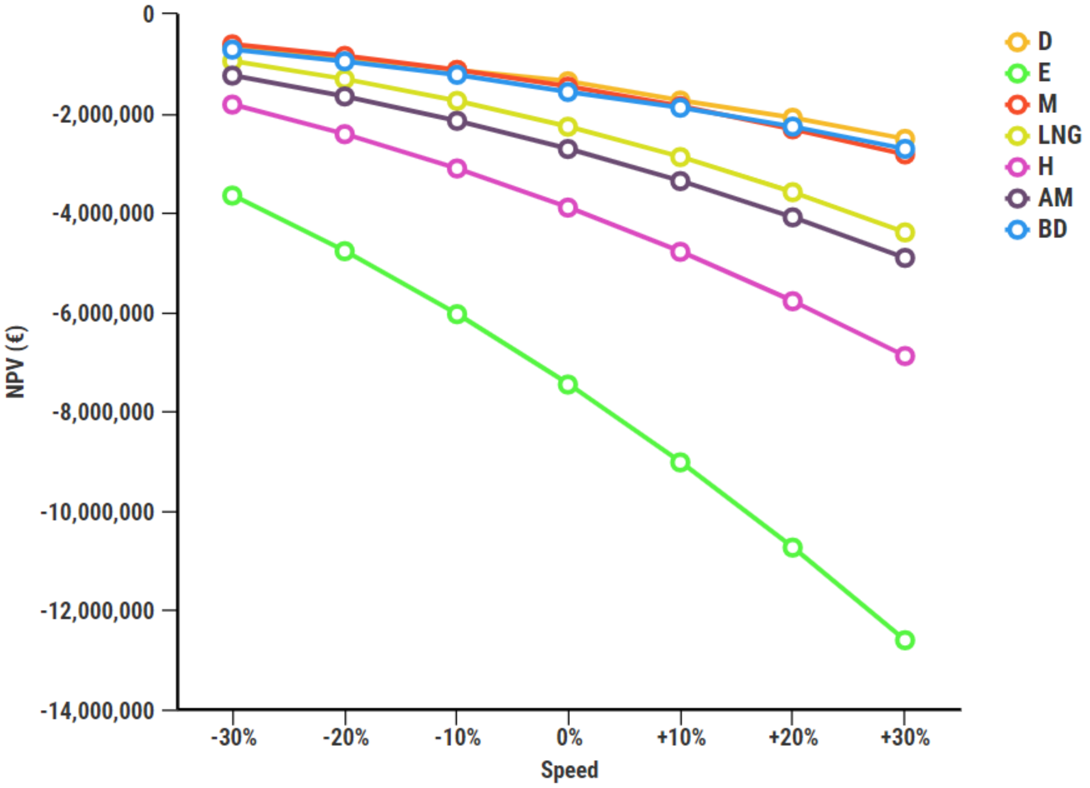

Fig. 17. Impact of ship speed on the *NPV* for different power systems; D - diesel, E - electricity, M - methanol, LNG - liquefied natural gas, H - hydrogen, AM - ammonia, BD - biodiesel-diesel blend B20

According to Fig. 17, an electric power system would be the most expensive solution for the cargo ship. However, by reducing the speed by 30%, the *NPV* of the electric-powered ship is reduced by 51%, while for the methanol-powered ship it is reduced by 56%. The main reason for this difference is the great investment cost of the electric-powered ship which is not discounted since it is an initial cost that occurs in year zero.

The analysis reveals that for most of the power systems, the cost of fuel has a major effect on the *NPV* and that by reducing the fuel costs, that is, with a fall in the price of fuel, the costs of the power system configurations become more acceptable. However, this does not refer to the electric-powered ship since the price of electricity is already low, while the investment cost is a major contributor to the total *NPV* of a system.

The sensitivity analysis indicates that the use of alternative fuels is more feasible when the speed is reduced, and when the total costs of alternative power systems are lower and therefore more acceptable to shipowners.

5. Conclusion

The decarbonisation of ship power systems through the use of alternative fuels is investigated in order to comply with ever stringent environmental regulations on the reduction of GHGs. The applicability of five alternative fuels (electricity, methanol, LNG, hydrogen, ammonia and biodiesel) is illustrated using the example of three different vessels belonging to the Croatian inland waterway fleet: a cargo ship, a passenger ship, and a dredger. The main conclusions of this research are:

- The LCA indicates that the most environmentally friendly option is an electric-powered vessel. This power system configuration results in a lower CF compared to the diesel power system configuration. The biggest CF reduction is achieved for the passenger ship, which amounts to 51%, while the cargo ship and the dredger achieved a CF reduction of 36% and 40%.
- The most cost-effective alternative is the one with the lowest total lifetime cost, which is a methanol power system configuration for the cargo ship. The LCCA highlighted that full electrification represents the most economical solution for the passenger ship, while for the dredger, the most economical option is still the diesel power system configuration.
- Even though methanol is shown as the most economical alternative fuel for the cargo ship, this study indicates that further development of the bunkering infrastructure and distribution chains of methanol are required. Since, for the dredger, the existing power system is the most cost-effective solution, one of the options is to replace diesel with methanol, leading to a power system that is only 15% more expensive than the existing one. Besides the required appropriate battery charger in ports, Li-ion battery technology is well known and commercially available, while the electricity for charging the battery is Croatian electricity. Therefore, an electric-powered ship is the most suitable option for the passenger ship.

Further investigation will focus on different hybrid power systems that can be applied in the Croatian inland waterway sector, taking into account more advanced solutions of a ship's power system, especially those with a high share of RESs. Their application, which depends on energy efficiency, i.e. environmental performance and cost-effectiveness, will be assessed with optimization methods.

Finally, it should be mentioned that although this model has been applied in the case of Croatia, it is generally applicable to other inland waterways if a relevant set of ship technical data, information on operating conditions, and insights into particular energy mixes of the considered country is available.

Acknowledgements

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Literature

[1] Monteiro A, Russo M, Gama C, Borrego C. How important are maritime emissions for the air quality: At European and national scale. Environmental Pollution 2018; 242 (Part A): 565-575.

[2] United Nations Framework Convention Climate Change. Climate Change Information kit, https://unfccc.int/resource/iuckit/cckit2001en.pdf; 2001 [accessed 10 July 2020].

[3] Toscano D, Murena F. Atmospheric ship emissions in ports: A review. Correlation with data of ship traffic. Atmospheric Environment: X 2019; 4: 100050.

[4] Keuken MP, Moerman M, Jonkers J, Hulskotte J, Denier van der Gon HAC, Hoek G, Sokhi RS. Impact of inland shipping emissions on elemental carbon concentrations near waterways in the Netherlands. Atmospheric Environment 2014; 95. 1-9.

[5] Wiegmans B, Witte P, Spit T. Inland port performance: a statistical analysis of Dutch inland ports. Transportation Research Procedia 2015; 8: 145-154.

[6] United Nations Economic Commission for Europe (UNECE). Efficient and sustainable inland water transport in Europe,

https://www.unece.org/fileadmin/DAM/trans/doc/2011/sc3wp3/ECE-TRANS-SC3-189e.pdf; 2011 [accessed 26 November 2020].

[7] United Nations. Transport Trends and Economics Series, Transport for Sustainable Development: The case of Inland Transport, https://www.unece.org/fileadmin/DAM/trans/publications/Transport_for_Sustainable_Development_UNECE_2015.pdf; 2015 [accessed 25 November 2020].

[8] Christodoulou A, Christidis P, Bisselink B. Forecasting the impacts of climate change on inland waterways. Transportation Research Part D: Transport and Environment 2020; 82: 102159.

[9] Xing S, Xinpig Y, Bing W, Xin S. Analysis of the operational energy efficiency for inland river ships. Transportation Research Part D: Transport and Environment 2013; 22: 34-39.

[10] Sys C, Van de Voorde E, Vanelslander T, van Hassel E. Pathways for a sustainable future inland water transport: A case study for the European inland navigation sector. Case Studies on Transport Policy 2020; 8: 686–699.

[11] European Commission. Transport emissions. A European Strategy for low-emission mobility, https://ec.europa.eu/clima/policies/transport_en; 2020 [accessed 25 November 2020].

[12] European Commission. Inland waterway, https://ec.europa.eu/transport/modes/inland_en; 2020 [accessed 12 July 2020].

[13] Cao Y-L, Wang X, Yin C-Q, Xu W-W, Shi W, Qian G-R, Xun Z-M. Inland Vessels Emission Inventory and the emission characteristics of the Beijing-Hangzhou Grand Canal in Jiangsu province. Process Safety and Environmental Protection, 2018; 113: 498-506.

[14] van der Zee SC, Dijkema MBA, van der Laan J, Hoek G. The impact of inland ships and recreational boats on measured NOx and ultrafine particle concentrations along the waterways. Atmospheric Environment 2012; 55: 368-376.

[15] Bataille C, Åhman M, Neuhoff K, Nilsson LJ, Fischedick M, Lechtenböhmer S, Solano-Rodriquez B, Denis-Ryan A, Steiber S, Waisman H, Sartor O, Rahbar S. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. Journal of Cleaner Production 2018; 187: 960-973.

[16] Environmental Protection Agency. Understanding the Global Warming Potentials, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials; 2020 [accessed 10 July 2020].

[17] Wiedmann T, Minx J. A Definition of Carbon Footprint. In: Pertsova CC, Ecological Economics Research Trends: Chapter 1. Nova Science Publishers, Hauppauge NY; 2008, 1-11.

[18] Bouman EA, Lindstad E, Rialland AI, Strømman AH. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping - A review. Transportation Research Part D: Transport and Environment 2017; 52: 408-421.

[19] Xing H, Spence S, Chen H. A comprehensive review on countermeasures for CO2 emissions from ships. Renewable and Sustainable Energy Reviews 2020; 134: 110222

[20] Hansson J, Månsson S, Brynolf S, Grahn M. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass and Bioenergy 2019; 126, 159-173.

[21] Livanos GA, Theotokatos G, Pagonis D-N. Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships. Energy Conversion and Management 2014; 79: 640–651.

[22] Fan A, Wang J, He J, Perčić M, Vladimir N, Yang L. Decarbonising inland ship power system: Alternative solution and assessment method. Energy 2021; 226: 120266.

[23] International Maritime Organization. Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility, http://www.imo.org/fr/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Report%20Methanol%2021.01.2016.pdf; 2016 [accessed 30 June 2020].

[24] Svanberg M, Ellis J, Lundgren J, Landälv I. Renewable methanol as a fuel for the shipping industry. Renewable and Sustainable Energy Reviews 2016; 94: 1217–1228.

[25] 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. Sustainable Production and Consumption 2020; 23: 236–248.

[26] Gilbert P, Walsh C, Traut M, Kesieme U, Pazouki K, Murphy. Assessment of full life-cycle air emissions of alternative shipping fuels. Journal of Cleaner Production 2018; 172: 855-866.

[27] Nuchturee C, Li T, Xia H. Energy efficiency of integrated electric propulsion for ships – A review. Renewable and Sustainable Energy Reviews 2020; 134: 110145.

[28] Perčić M, Ančić I, Vladimir N. Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector. Renewable and Sustainable Energy Reviews 2020; 131:110028.

[29] Gagatsi E, Estrup T, Halatsis A. Exploring the potentials of electrical waterborne transport in Europe: the E-ferry concept. Transportation Research Procedia 2016; 14: 1571-1580.

[30] EU Emissions Trading System. Carbon allowance, https://ec.europa.eu/clima/policies/ets_en; 2020 [accessed 09 July 2020].

[31] Trapp AC, Harris I, Sanchez Rodrigues V, Sarkis J. Maritime container shipping: Does coopetition improve cost and environmental efficiencies? Transportation Research Part D 2020; 87: 102507.

[32] van Biert L, Godjevac M, Visser K, Aravind PV. A review of fuel cell systems for maritime applications. Journal of Power Sources 2016; 327: 345-364.

[33] Abdin Z, Zafaranloo A, Rafiee A, Mérida W, Lipiński W, Khalilpour KR. Hydrogen as an energy vector. Renewable and Sustainable Energy Reviews 2020; 120: 109620.

[34] Prussi M, Scarlat N, Acciaro M, Kosmas V. Potential and limiting factors in the use of alternative fuels in the European maritime sector. Journal of Cleaner Production 2021; 291: 125849.

[35] Perčić M, Vladimir N, Fan A. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia. Applied Energy 2020; 279: 115848.

[36] Nair A and Acciaro M. Alternative fuels for shipping: optimising fleet composition under environmental and economic constraint. International Journal of Transport Economics 2018; XLV.

[37] International Energy Agency. Croatia, CO_2 emissions by sector, https://www.iea.org/countries/croatia; 2020 [accessed 30 November 2020].

[38] Ministry of environment and energy, Republic of Croatia. Croatian greenhouse gas inventory for the period 1990 – 2018 (National Inventory Report 2020), http://www.haop.hr/sites/default/files/uploads/dokumenti/012_klima/dostava_podataka/Izvjesca/NIR_2020_eng.pdf; 2020 [accessed 30 November 2020].

[39] Ministry of Economy and Sustainable Development, Republic of Croatia. Low-Carbon Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050, https://mzoe.gov.hr/o-ministarstvu-1065/djelokrug-4925/klima/strategije-planovi-i-programi-1915/strategija-niskougljicnog-razvoja-hrvatske/1930; 2020 [accessed 01 December 2020].

[40] Ministry of the Sea, Transport and Infrastructure of the Republic of Croatia. Inland navigation, https://mmpi.gov.hr/more-86/unutarnja-plovidba-110/110; 2020 [accessed 25 June 2020].

[41] Croatian Register of Shipping. Register of inland waterway vessels. http://www.crs.hr/Portals/0/Register%20of%20Inland%20Navigation%20Vessels.pdf; 2019 [accessed 25 June 2020].

[42] The cargo ship “Opatovac”. https://www.marinetraffic.com/en/ais/details/ships/shipid:209454/mmsi:238401840/imo:0/vessel:OPATOVAC; 2020 [accessed 07 November 2019].

[43] National Park Krka. Passenger ship “Trošenj”. http://www.npkrka.hr/stranice/izleti-brodom/33.html, http://www.npkrka.hr/stranice/ulaz-skradin/30.html; 2020 [accessed 26 June 2020].

[44] Dredger “Papuk”. http://www.hidrogradnja.hr/gallery/papuk/; 2020 [accessed 09 July 2019].

[45] van Essen HP, Faber J, Wit RCN. Charges for barges? Preliminary study of economic incentives to reduce engine emissions from inland shipping in Europe, Delft, CE; 2004.

[46] Croatian Meteorological and Hydrological Service. Hydrology sector, https://hidro.dhz.hr/; 2020 [accessed 26 June 2020].

[47] Ančić I, Vladimir N, Cho DS. Determining environmental pollution from ships using Index of Energy Efficiency and Environmental Eligibility (I4E). Marine Policy 2018; 95: 1-7.

[48] International Organization for Standardization (ISO 14040). Life cycle assessment, https://web.stanford.edu/class/cee214/Readings/ISOLCA.pdf; 1997 [accessed 09 July 2020].

[49] GREET. LCA software, https://greet.es.anl.gov/; 2020 (accessed 27 June 2020].

[50] IMO. Third IMO GHG Study, Executive Summary and Final Report. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf; 2014 [accessed 18 March 2020].

[51] Ellis J, Tanneberger K. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. Report prepared for the European Maritime Safety Agency (EMSA), 2015.

[52] Croatian Energy Regulatory Agency. Annual Report, https://www.hera.hr/en/docs/HERA_Annual_Report_2018.pdf; 2018 [accessed 29 June 2020].

[53] Zubi G, Dufo-López R, Carvalho M, Pasaoglu G. The lithium-ion battery: State of the art and future perspectives. Renewable and Sustainable Energy Reviews 2018; 89: 292-308.

[54] Gandoman FH, Jaguemont J, Shovon Goutam S, Gopalakrishnan R, Firouz Y, Kalogiannis T, Omar N, Van Mierlo J. Concept of reliability and safety assessment of lithium-ion batteries in electric vehicles: Basics, progress, and challenges. Applied Energy 2019; 251: 113343.

[55] HEP. Sources for Croatian electricity generation, http://www.hep.hr/elektra/trziste-elektricne-energije/izvori-elektricne-energije/1553#; 2020 [accessed 09 July 2020].

[56] Ammar NR. An environmental and economic analysis of methanol fuel for a cellular container ship. Transportation Research Part D: Transport and Environment 2019; 69: 66-76.

[57] MAN. The ME-LGI Engine and Methanol as a Marine Fuel, https://marine.man-es.com/two-stroke/2-stroke-engines/me-lgim; 2020 [accessed 30 June 2020].

[58] MAN. Marine engine programme, https://www.man-es.com/docs/default-source/marine/4510_0017_02web.pdf?sfvrsn=4e9c62f7_12; 2019 [accessed 30 June 2020].

[59] Methanex. Methanol, https://www.methanex.com/about-methanol; 2020 [accessed 30 June 2020].

[60] Wan C, Yan X, Zhang D, Yang Z. A novel policy making aid model for the development of LNG fuelled ships. Transportation Research Part A: Policy and Practice 2019; 119: 29–44.

[61] Wärtsilä,. Dual- fuel engines, https://www.wartsila.com/encyclopedia/term/dual--fuel-engines-from-w%C3%A4rtsil%C3%A4; 2020 [accessed 01 July 2020].

[62] Ekanem Attah E, Bucknall R. An analysis of the energy efficiency of LNG ships powering options using the EEDI. Ocean Engineering 2015; 110: 62-74.

[63] Wärtsilä, 34DF, product guide, https://www.wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w34df.pdf?utm_source=engines&utm_medium=dfengines&utm_term=w34df&utm_content=productguide&utm_campaign=msleadscoring; 2019 [accessed 01 July 2020].

[64] Bicer Y, Dincer I. Clean fuel options with hydrogen for sea transportation: A life cycle approach. International Journal of Hydrogen Energy 2018; 43: 1179-1193.

[65] Inal BO, Deniz C. Assessment of fuel cell types for ships: Based on multi-criteria decision analysis. Journal of Cleaner Production 2020; 265: 121734.

[66] Rivarolo M, Rattazi D, Lamberti T, Magistri L. Clean energy production by PEM fuel cells on tourist ships: A time-dependent analysis. International Journal of Hydrogen Energy 2020. https://doi.org/10.1016/j.ijhydene.2019.12.086.

[67] Garraı´n D, Lecho´n Y. Exploratory environmental impact assessment of the manufacturing and disposal stages of a new PEM fuel cell. International Journal of Hydrogen Energy 2014; 39 (4): 1769-1774.

[68] Cha J, Jo YS, Jeong H, Han J, Nam SW, Song KH, Yoon CW. Ammonia as an efficient COX-free hydrogen carrier: Fundamentals and feasibility analyses for fuel cell applications. Applied Energy 2018; 224: 194–204.

[69] Chisalita D-A, Petrescu L, Cormos C-C. Environmental evaluation of european ammonia production considering various hydrogen supply chains. Renewable and Sustainable Energy Reviews 2020; 130: 109964.

[70] Kim K, Roh G, Kim W, Chu K. A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering 2020; 8(3): 183.

[71] Mohd Noor CW, Noor MM, Mamat R. Biodiesel as alternative fuel for marine diesel engine applications: A review. Renewable and Sustainable Energy Reviews 2018; 94: 127–142.

[72] Demirbas A. Progress and recent trends in biodiesel fuels. Energy Conversion and Management 2009; 50 (1): 14-34.

[73] Buratti C, Barbanera M, Fantozzi F. A comparison of the European renewable energy directive default emission values with actual values from operating biodiesel facilities for sunflower, rape and soya oil seeds in Italy. Biomass and Bioenergy 2012; 47: 26-36.

[74] Hammond GP, Seth SM. Carbon and environmental footprinting of global biofuel production. Applied Energy 2013; 112: 547-559.

[75] Trivyza NL, Rentizelas A, Theotokatos G. Impact of carbon pricing on the cruise ship energy systems optimal configuration. Energy 2019; 175: 952-966.

[76] International Energy Agency. World Energy Outlook 2019. https://doi.org/10.1787/caf32f3b-en.

[77] Iannaccone T, Landucci G, Tugnoli A, Salzano E, Cozzani V. Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. Journal of Cleaner Production 2020; 260: 121069.

[78] European Commission. Energy prices and costs in Europe, Annex 3, https://ec.europa.eu/energy/sites/ener/files/documents/annex_3_-_country_sheets_-part_4_of_4_post_isc-v2.pdf; 2018 [accessed 07 July 2020].

[79] Christos B. Techno-economical feasibility study on the retrofit of double-ended Ro/Pax ferries into battery-powered ones. Diploma thesis. National Technical University of Athens, School of Naval Architecture and Marine Engineering; 2017.

[80] Tsiropoulos I, Tarvydas D, Lebedeva N. Li-ion batteries for mobility and stationary storage applications, JCR Science for Policy Report, European Commission. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113360/kjna29440enn.pdf; 2018 [accessed 07 July 2020].

[81] Ghenai C, Bettayeb M, Brdjanin B, Hamid AK. Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ship: A case study in Stockholm, Sweden. Case Studies in Thermal Engineering 2019; 14: 100497.

[82] Niaz S, Manzoor T, Pandith AH. Hydrogen storage: Materials, methods and perspectives. Renewable and Sustainable Energy Reviews 2015; 50: 457–469.

[83] Ma S, Lin M, Lin T-E, Lan T, Liao X, Maréchal F, Van Herle J, Yang Y, Dong C, Wang L. Fuel cell-battery hybrid systems for mobility and off-grid applications: A review. Renewable and Sustainable Energy Reviews 2021; 135: 110119.

[84] European Commission. Fuel price comparison, https://ec.europa.eu/transport/sites/transport/files/2017-01-fuel-price-comparison.pdf; 2017 [accessed 15 July 2020].

[85] International Renewable Energy Agency (IRENA). Hydrogen from renewable power: Technology outlook for the energy transition, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf; 2018 [accessed 06 May 2021].