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Maja Perčić[1*], Nikola Vladimir[1], Ivana Jovanović[1], Marija Koričan[1]

[1]University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10002 Zagreb, Croatia. * Corresponding author: maja.percic@fsb.hr

Abstract

This paper investigates the viability of different fuel cell types in a ship power system, where hydrogen and ammonia are considered as zero-carbon fuels. The identification of alternatives to diesel-powered ships is performed by taking into account the environmental and economic indicators of the considered power systems, determined by Life-Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA), and further compared with the existing diesel power systems of three passenger ships operating in Croatian coastal waters. Special attention is paid to fuel origin, where fossil fuels (grey fuel), fossil fuels followed by CO_2 capture (blue fuel), and those produced from renewable energy sources (green fuel) are considered. The results of the research indicate that fuel cell systems with grey hydrogen and grey ammonia are not environmentally friendly, while fuel cell systems with the blue and green types of these fuels have a lower impact on the environment than a diesel-powered ship, with a reduction of up to 84% in CO_2-eq emissions when green ammonia is used. Regarding profitability, the diesel-powered ship has the lowest total costs, while the second most cost-effective option is the fuel cell system with blue ammonia as fuel with 27%-43% higher costs than a diesel-powered ship, depending on which type of fuel cell is used. Although blue ammonia is a cheaper fuel than diesel fuel, the lifetime costs of the fuel cell power system are affected by relatively high investment costs (fuel cell, battery, cracker, etc.) and equipment replacement costs.

Keywords: short-sea shipping; fuel cell; ammonia; hydrogen; LCA; LCCA

Nomenclature

Variables

AFP	aerosol formation potential (t PM 2,5 -eq)
AP	acidification potential (t SO_2-eq)
BC	battery capacity (kWh)
CapEx	capital costs (€)
E	emission (t)
EC	energy consumption (kWh/nm)
EF	emission factor (g emission/kg)
EH	energy for heating of a fuel cell system (kWh)
FC	fuel consumption (kg/nm)
FED	fossil energy demand (%)
GWP	global warming potential (t CO_2-eq)
l	length of one-way trip (nm)
LM	lifetime mileage (nm)
LT	lifetime (year)
n	time of a ship lifetime (year)
N	number of round trips (-)
NCV	net calorific value (kWh/kg)
NPV	net present value (€)
OpEx	operating costs (€)
P	power (kW)
r	discount rate (%)
SFC	specific fuel consumption (kg/kWh)
t	operational time (h)
v	speed (kn)

Greek letters

η	efficiency (-)

Abbreviations

B-A	Blue ammonia
B-H	Blue hydrogen
CCS	Carbon Capture and Storage
ECA	Emission Control Area
DAFC	Direct Ammonia Fuel Cell
EEDI	Energy Efficiency Design Index
GH2	Gaseous hydrogen
GHG	Greenhouse gas
Gn-A	Green ammonia
Gn-H	Green hydrogen
Gy-A	Grey ammonia
Gy-H	Grey hydrogen
IMO	International Maritime Organization
KPI	Key Performance Indicator
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Assessment
LH2	Liquid hydrogen
M	Manufacturing phase
MCFC	Molten Carbonate
PEMFC	Proton Exchange Membrane Fuel Cell
PTW	Pump-to-Wake phase
RES	Renewable Energy Source
SD	Sustainable Development
SOFC	Solid Oxide Fuel Cell
WROS	World Register of Ships
WTP	Well-to-Pump phase

Subscripts

A	ammonia
AE	auxiliary engine
An	annual
ave	average
B	battery-powered ship
C	cracker
CH_4	emission of methane
CO_2	emission of carbon dioxide
D	diesel-powered ship
de	design
f	fuel used in a fuel cell
FC	fuel cell
H	hydrogen
i	any emission
M,i	emission *i* from M phase
ME	main engine
NO_X	emission of nitrogen oxides
N_2O	emission of nitrous oxide
P	purifier
PEMFC-A	PEMFC fueled with ammonia
PM10	emission of particulate matter
PEMFC-H	PEMFC fueled with hydrogen
PTW,i	emission *i* from PTW phase
SOFC-A	SOFC fueled with ammonia
SO_X	emission of sulphur oxides
SOFC-H	SOFC fueled with hydrogen
st	start-up
WTP, i	emission *i* from WTP phase

1. Introduction

Fossil fuel combustion in a ship's internal combustion engine causes exhaust gas consisting of nitrogen oxides (NO_X), sulphur oxides (SO_X), carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM), and hydrocarbons [1]. In order to control these emissions which negatively affect the environment and human health [2], the International Maritime Organization (IMO) within the International Convention for the Prevention of Pollution from Ships set regulations for the prevention of air pollution from ships, including the establishment of Emission Control Areas (ECAs) [3]. SO_X emissions are regulated by the limit of sulphur content in fuel, while the NO_X emission limit depends on the engine maximum operating speed. Both the SO_X and NO_X regulation standards differ depending on the area of navigation (global or ECA) [4]. CO_2 emissions are regulated by the Energy Efficiency Design Index (EEDI), which represents the ratio between the released amount of CO_2 emissions and the benefit for society [5].

CO_2 is the major Greenhouse Gas (GHG) and an increase in its concentration in the atmosphere causes global warming [6]. Within the scope of the Paris Agreement adopted in 2015 which advocates the reduction of GHGs [7], IMO set a goal of reducing GHG emissions from international shipping by 50% up to 2050 compared to the 2008 levels [8]. In the most recent GHG Study, [9], IMO reported that in 2018 the shipping sector generated 2.89% of global anthropogenic GHG emissions, while in 2012 this share was 2.76%. The study predicts that without proper and rigorous decarbonization measures, GHG emissions from shipping will rise [9]. GHG reduction measures and technologies are presented in studies by Bouman et al. [10] and Xing et. al. [11]. According to these authors, the replacement of a conventional power system with alternatives will lead to a significant reduction in shipping emissions. One alternative is electrification, where three different types of electrified ships can be identified: a fully electric ship, a plug-in hybrid ship, and a hybrid electric ship. These ships use a small or zero amount of fossil fuel, which results in lower maintenance costs, increased safety, and reduced noise and vibrations, leading to lower disruption of the marine ecosystem [12]. Due to the absence of exhaust gases, the most environmentally friendly type of electrification is full electrification [13]. One of the powering options is a rechargeable battery, where the Lithium-ion (Li-ion) battery is perhaps the most significant for the shipping industry, currently having the highest energy density among other commercial batteries [14]. Besides battery, fully electric propulsion can also be achieved by means of fuel cell technology onboard the ship [15], which represents an important and viable solution for zero-carbon shipping [16]. While battery-powered ships exploiting current technology are nowadays suitable only for coastal navigation [13], fuel cell technology has the potential to be used on large and high-power ships that operate on the open seas [17]. With the further development of battery technology towards metal-air batteries with a much higher energy density and lifetime than the Li-ion battery [18], the full electrification of ships operating on longer routes using only a battery may be feasible.

A fuel cell is an electrochemical device that converts the chemical energy of fuel into electric energy. The basic elements of a fuel cell are a positive electrode (cathode), a negative electrode (anode) and an electrolyte. Fuel enters into the anode and an oxidant into the cathode. Due to the electrochemical reaction of oxidation and reduction, a gradient of chemical potential is developed, resulting in electricity in the external electrical circuit [19]. Different fuel cell types are available, and they are primarily classified by their operating temperature and by the electrolyte used, i.e. their names reflect the materials used in the electrolyte. Based on the operating temperature, fuel cells can be classified into three groups: low-temperature fuel cells (~80°C), intermediate-temperature fuel cells (~200°C), and high-temperature fuel cells (650°C-1000°C) [20].

Hydrogen is an ideal fuel for a fuel cell, due to its fast kinetics of electrochemical reactions and the absence of exhaust gases, where the only by-product of the reaction is water [21]. Based on cleanliness and the type of energy used for its production, hydrogen can be classified into three types: grey, blue, and green hydrogen. Grey hydrogen is produced from fossil fuels and results in a substantial amount of CO_2 emissions. Blue hydrogen is also produced from fossil fuels, but the Carbon Capture and Storage (CSS) technology reduces the released CO_2 emissions, while green hydrogen is a sustainable and clean fuel produced from Renewable Energy Sources (RESs) [22], [23]. Nowadays, hydrogen is mostly produced by the process of steam reforming methane from natural gas, while nearly 4% of global hydrogen is produced via electrolysis. This production technology uses electricity to produce hydrogen from water, resulting in CO_2 emissions related to electricity generation, which depend on the electricity mix used [24]. Madsen et al. [25] investigated the feasibility of a fuel-cell-powered coastal research ship with green hydrogen produced via electrolysis. The research showed around 91% fewer life-cycle GHGs in comparison with a diesel-powered ship. However, by using grey hydrogen instead of green hydrogen, the overall life-cycle emissions would be higher than those of a diesel-powered ship. Recent studies on CO_2

mitigation consider the use of green hydrogen to transform captured CO_2 into synthetic liquid fuels, such as synthetic natural gas. In this way, CO_2 is recycled, contributing to achieving the aim of global carbon neutrality [26], [27].

The major drawback of the use of hydrogen onboard is its storage, mainly due to its low density. Onboard storage options vary from a cryogenic tank with liquid hydrogen (LH2), metal hydride storage at an ambient temperature, and a gaseous hydrogen (GH2) tank. While GH2 storage is small-scale and is used for mobile applications, LH2 storage represents medium large storage for shipping purposes. By using LH2 instead of GH2, the tank size and costs decline [28]. In order to avoid storage issues, hydrogen can be produced onboard [29], either through the use of electricity and water by electrolysis [30], or through the use of hydrogen carriers, i.e. fuels that contain hydrogen [31]. The latter option simplifies the fuel supply chain and infrastructure since hydrogen carriers are more readily available and there are fewer problems with storage than with pure hydrogen. Hydrogen carriers are usually natural gas, methanol, ethanol, ammonia etc. [32].

Ammonia is particularly attractive since it is a carbon-free and hydrogen-rich fuel that can be easily liquefied. Along with an already established storage and transportation infrastructure, ammonia is highlighted as an economical fuel that can be used in fuel cells [33], [34]. However, ammonia is toxic, and potential leakage represents a key safety concern for its use as a marine fuel [35]. Ammonia is the second most produced chemical in the world, which serves mainly as a fertilizer. It is mainly produced through the Haber-Bosch process, where nitrogen from the air and hydrogen are combined under high temperature and pressure. Depending on its cleanliness and the way it is produced, grey, blue and green ammonia can be distinguished [36], [37].

Although each type of fuel cell can use hydrogen as a fuel, low-temperature fuel cells, i.e. the Proton Exchange Membrane Fuel Cell (PEMFC), cannot use hydrogen carriers. Besides, PEMFC requires pure hydrogen due to its sensitivity to impurities, i.e. CO can contaminate the platinum catalyst in a fuel cell [38]. Unlike high-temperature fuel cells, which provide internal fuel processing, the PEMFC requires pure hydrogen, or other fuel needs to undergo different types of fuel processing, depending on its constituent parts, e.g. hydrocarbons such as natural gas and methanol need to undergo reforming processes and a purifying process, while ammonia requires decomposition and a purifying process [39].

High-temperature fuel cells, such as the Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC), offer several advantages regarding power generation, i.e. high efficiency, low noise, stable power output, and fuel flexibility [40]. The MCFC is a mature and expensive technology with low power density. The SOFC offers high power density, the potential to be incorporated in a system with a gas turbine, although mechanical vulnerability and high costs limit its wider application [31]. The major safety concerns of fuel cells are related to high-temperature fuel cells and the temperature of their exhaust gas, for which the proper insulation of pipes is required to prevent leakage. Therefore, in terms of safety, low-temperature fuel cells have an advantage over high-temperature ones, mainly due to the lower operating temperature [41]. However, the use of pure hydrogen is associated with a set of other requirements due to its flammability, potential for explosion, and its potential to the embrittle materials [42].

Fuel cell technology can be used for stationary and mobile applications, where it faces several challenges such as fuel supply and storage, complex design, high investment costs, etc. In addition, the technology for large-scale applications is not yet mature. Many attempts have been made to implement fuel cell technology in the maritime sector [43]. However, efforts primarily focus on using fuel cells to cover the auxiliary needs of ships by combining them in a hybrid power system. For example, Sapra et al. [44] presented the integration of a fuel cell with an internal combustion engine for use onboard long-distance ships, while Ahn et al. [45] investigated a hybrid power system, consisting of a marine generator, an SOFC and gas turbine onboard a large ethane carrier. Díaz-de-Baldasano et al. [46] focused on the design and integration of a methanol-fed SOFC with a diesel generator in a ship power system installed onboard an offshore platform supply vessel. In total, 20% of energy needs were covered by the fuel cells.

Recent studies indicate interest in using fuel cells for ship propulsion. Wu and Bucknall focus on the modelling of a plug-in hybrid PEMFC/battery propulsion system for a coastal ferry and concluded that this kind of system can significantly reduce GHGs. However, high costs remain an issue [47]. Choi et al. [48] also investigate the ship power system with an integrated PEMFC and battery. Their study presents the detailed development of such a system onboard a ferry in Busan, South Korea. A PEMFC is indicated as a suitable onboard fuel cell for ships that operate near the shore and close to refueling tanks, while an SOFC is a potential candidate for high-power ships such as cargo ships and cruise ships[17]. Perčić et al. [49] performed an economic and environmental analysis of the use of alternative powering options for ships, among which a PEMFC with grey hydrogen is highlighted as the poorest environmental and economic alternative to replace the conventional diesel power system. However, grey hydrogen production requires fossil fuel, and it results in a high amount of pernicious emissions released into the atmosphere. Therefore, the exploitation of different fuel cells, different hydrogen carriers, and types of fuel with regard to production processes, i.e. grey, blue and green types of fuel, should be further investigated to obtain a fair insight into the feasibility of fuel cell technology in the shipping sector.

Based on the above literature overview, knowledge gaps are indicated as follows:

- Studies on fuel cell systems as a ship's sole powering option are limited since most are oriented only to the auxiliary energy needs of the ship.
- There is a lack of studies that simultaneously include an environmental and economic analysis of different types of fuel cells used in power systems onboard ships over their lifetime. To the best of the authors' knowledge, there are no studies offering a comparison of the lifetime emissions and costs of fuel-cell-powered vessels and conventional diesel-powered vessels in coastal navigation, which is the most suitable for the implementation of innovative powering solutions.
- Research into zero-carbon fuels for waterway transportation, which takes into account their different production paths, is lacking. Most studies investigate either hydrogen or ammonia, but usually they are not specified as grey, blue or green hydrogen or ammonia. So, both the environmental benefit and economic potential of these fuels are not clear for marine applications.
- To the best knowledge of the authors, there are no studies that take into account different options of heating the fuel cell within the scope of marine applications. This is a highly important issue in coastal navigation, particularly for vessels with strict navigation schedules, like ferries, passenger ships, etc.

In this paper, the environmental and economic aspects of ships powered by PEMFCs and SOFCs are investigated where zero-carbon fuels (hydrogen and ammonia) are used. As a test case, the Croatian short-sea shipping fleet is chosen, where three ferries that operate on different routes are selected. These kinds of ships represent appropriate test cases to investigate the applicability of new technologies in the shipping sector due to the moderate energy requirements and the proximity to the shore. A preliminary analysis indicated that 44 Croatian ferries operate on 23 domestic and 3 international lines (connecting Croatia with

Italy) [50]. The application of technologies that result in no emissions, such as fuel cells fueled with zero-carbon fuels, besides having a lower environmental impact, results in a reduction in the negative effect on human health, which is more pronounced when the ships, like coastal vessels, operate near populated areas. The global impact of fuel cells onboard such ships can be found in data obtained from the World Register of Ships (WROS) database [51], according to which 3,123 ferries are in service globally. Based on passenger and vehicle capacity, total engine power and dimensions, the WROS database indicates 626 ships that are similar to those selected for this paper.

By performing Life-Cycle Assessments (LCAs) and the Life-Cycle Cost Assessments (LCCAs) of different fuel cell configurations, their environmental and economic indicators are calculated and compared to the existing diesel power system configuration. Based on this comparison, viable fuels and fuel cell types that ensure lower emissions at reasonable costs are highlighted. The contributions of this paper are summarized as follows:

- Development of a model for the application of particular zero-carbon fuel in PEMFCs and SOFCs on board ro-ro passenger ships and used as the only power source satisfying total ship energy needs.
- Identification of feasible fuel cell power systems with particular fuels onboard Croatian ro-ro passenger ships that satisfy environmental and economic criteria, bearing in mind future emission targets [9].
- Environmental and economic analysis of zero-carbon fuels, i.e. hydrogen and ammonia, and their grey, blue and green types implemented in a fuel cell.
- Development of a model for onshore and onboard heating of both PEMFCs and SOFCs.

The importance of the considered problem derives from the fact that, excluding nuclear power, the only options for zero-emission power production onboard ships are batteries and fuel cells.

2. Methodology

2.1. Ship data

The selected ships engaged in the Croatian short-sea shipping fleet are three ro-ro passenger ships, i.e. ferries that operate on short (Ship 1), medium (Ship 2), and relatively long routes (Ship 3) [49]. The ships are powered by conventional power systems, i.e. diesel engines. Their main particulars are presented in Table 1, and are obtained from the Croatian Register of Shipping [52], while the shipping schedules are taken from [53].

Table 1 Main ship particulars [49], [52], [53],

	Ship 1	Ship 2	Ship 3
Route	Prizna-Žigljen	Ploče-Trpanj	Vis-Split
Ship name	Prizna	Kornati	Petar Hektorović
Length between perpendiculars (m)	52.4	89.1	80
Breadth (m)	11.7	17.5	18.0
Draught (m)	1.63	2.40	3.80
Main engine(s) power, P_{ME} (kW)	792	1,764	3,600
Auxiliary engine(s) power, P_{AE} (kW)	84	840	1,944
Design speed, v_{de} (kn)	8.0	12.3	15.75
Passenger capacity	300	616	1,080
Vehicle capacity	60	145	120
Trip duration, t (min)	15	60	140
Route length, l (nm)	1.61	8.15	30.2
Annual number of return trips, N_{An}	1,590	1,740	800

The ships are designed to navigate at operating speeds, v_{de} (kn), which correspond to 70%–80% of the main engine load [54]. However, the operating speed of a ship is variable, depending on the weather conditions (e.g. waves), keeping to the schedule, voluntary speed reduction (slow steaming), etc. Therefore, based on the data on route length, l (nm), and its duration, t (h), the average ship speed, v_{ave} (kn), can be calculated.

By following up the cubic relationship between ship speed and power, the average main engine power, $P_{ME,ave}$ (kW), was calculated according to the following equation:

$$P_{ME,ave} = (P_{ME} \cdot 0.8) \cdot \left(\frac{v_{ave}}{v_{de}}\right)^3. \tag{1}$$

Assuming that the average load of the auxiliary engine, $P_{AE,ave}$ (kW), is 50%, the total average ship power, P_{ave} (kW), is calculated by summing $P_{ME,ave}$ and $P_{AE,ave}$. The energy consumption per distance, EC_D (kWh/nm), of an existing diesel-powered ship is then calculated according to:

$$EC_D = \frac{P_{ave}}{v_{ave}}. \tag{2}$$

It is assumed that a common lifetime (*LT*) of a conventional power system is 20 years. Hence, the environmental and economic performances of different ship power systems over 20 years are investigated.

2.2. Key performance indicators

In this paper, Key Performance Indicators (KPIs) are quantifiable values that reflect the environmental and economic performance of a ship power system [55]. Bearing in mind the extensive use of fossil fuel in the maritime sector, whose combustion generates different emissions, the environmental KPIs are defined by taking into account the released emissions and consumed fossil energy.

The increased concentration of anthropogenic GHGs in the atmosphere represents a growing problem for the global community. Since GHGs are a mixture of different gases where CO_2 is the major one, while methane (CH_4) and nitrous oxide (N_2O) are present in a lower concentration, they each make a different contribution to global warming [6]. An evaluation of their contribution is performed by involving the Global Warming Potential (*GWP*), which is a measure of how much energy the emission of one ton of a gas will absorb over a given period relative to the emission of 1 ton of CO_2. Therefore, by using the CO_2-equivalent (CO_2-eq) factors over 100 years (CO_2: 1; CH_4: 36; N_2O: 298) [56], the environmental KPI within the impact category of climate change, *GWP*, is calculated according to the following equation:

$$GWP = 1 \cdot E_{CO_2} + 36 \cdot E_{CH_4} + 298 \cdot E_{N_2O}, \tag{3}$$

where *E* refers to the released emissions of a particular gas.

Shipping emissions can negatively affect both terrestrial and aquatic ecosystems through eutrophication and acidification. The SO_2 and NO_X emissions from the atmosphere fall to the ground in the form of acid rain/snow/mist and affect waters and soil, which consequently affect the level of nutrients in the body of water by causing eutrophication [57]. Therefore, the Acidification Potential (*AP*) is another environmental KPI. The *AP*, expressed in SO_2-eq, is calculated by multiplying the emissions of a particular acidifying gas by the SO_2-equivalence factors (NO_X: 0.7; SO_X: 1), as in the following equation:

$$AP = 1 \cdot E_{SOx} + 0.7 \cdot E_{NOx}. \tag{4}$$

Since the emissions of SO_X, NO_X and PM affect the formation of aerosol, which has a negative impact on human health, the Aerosol Formation Potential (*AFP*) is included as another environmental KPI. It is calculated by multiplying the emission quantities with PM 2.5 equivalence factors (PM 10: 0.5; SO_X: 0.54; NO_X: 0.88) [58]:

$$AFP = 0.5 \cdot E_{PM10} + 0.54 \cdot E_{SOx} + 0.88 \cdot E_{NOx}. \tag{5}$$

With the depletion of fossil fuels and moving towards sustainable energy resources, the considered KPI of Fossil Energy Demand (*FED*) is included in the analysis as the share of the fossil energy consumed.

As for the economic performance of a ship power system, the KPI of Net Present Value (*NPV*) is selected since it represents the total costs of the power system, discounted to the present value.

The KPIs are observed from the life-cycle point of view, where environmental KPIs are obtained by performing the LCA, while economic KPI is calculated within the LCCA. The selected KPIs are presented in Figure 1.

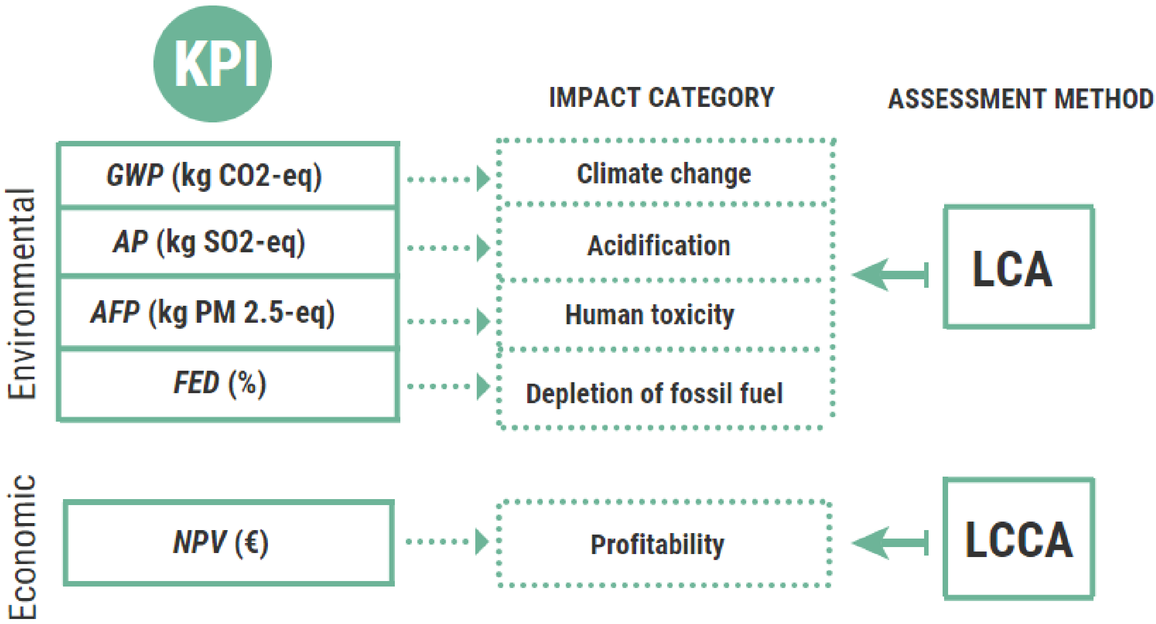

Figure 1. The defined KPIs

2.3. In general about life-cycle assessment

Increased awareness of atmospheric pollution and its negative effects encourages analysis of the environmental performance of a product. LCA is a technique for the analysis of the energy consumed and emissions released through each stage of the life cycle of a product, i.e. from the extraction of the raw material, the production of a product, the product's use, and the final disposal or/and recycling process [59].

By following the guidelines of ISO 14040 [59] and ISO 14044 [60], performing the LCA also requires a definition of the goal and the scope of the assessment, the functional unit, the system boundary and the life-cycle inventory. In this paper, LCA offers insight into the feasibility of different powering options of three ships by comparing the released emissions and energy consumed throughout the life cycle of a power system. Therefore, the system boundary is set on the ship power system. In the assessment, different environmental impact categories are investigated. The functional unit, which enables the investigated power systems to be compared, is the lifetime mileage (*LM*) of each considered ship, calculated according to the following equation:

$$LM = LT \cdot N_{An} \cdot 2 \cdot l, \tag{6}$$

where N_{An} refers to the annual number of round trips, and l refers to the length of a one-way trip.

LCA is performed by means of the LCA software GREET 2020 [61], whose database contains many processes, fuel, and materials, primarily intended for the land transportation sector. Since the primary focus of the analysis is on the ship power system, the emissions and energy consumed are easily calculated by GREET 2020. The observed emissions and energy through the life cycle are divided into three categories. The first represents the Well-to-Pump (WTP) phase which includes the processes of raw material extraction, the production of fuel and its transportation to a pump. The second is the Pump-to-Wake (PTW) phase which refers to the use of a product, and, in this case, the use of fuel for the ship to operate. The third phase is the Manufacturing (M) phase which considers the emissions released and the energy consumed during the manufacturing of the main power system elements (battery, engine, fuel cell, etc.).

2.4. In general about life-cycle cost assessment

An economic analysis of different ship power systems highlights the most cost-effective powering option to be implemented on a particular ship [62]. In this paper, the total costs during the ship lifetime of 20 years are considered, and they are divided into two groups, i.e. *CapEx* and *OpEx*. *CapEx* represents the investment (capital) cost of a power system, while *OpEx* relates to the costs of the ship power system operation, i.e. fuel cost, maintenance cost, and equipment replacement cost, Figure 2.

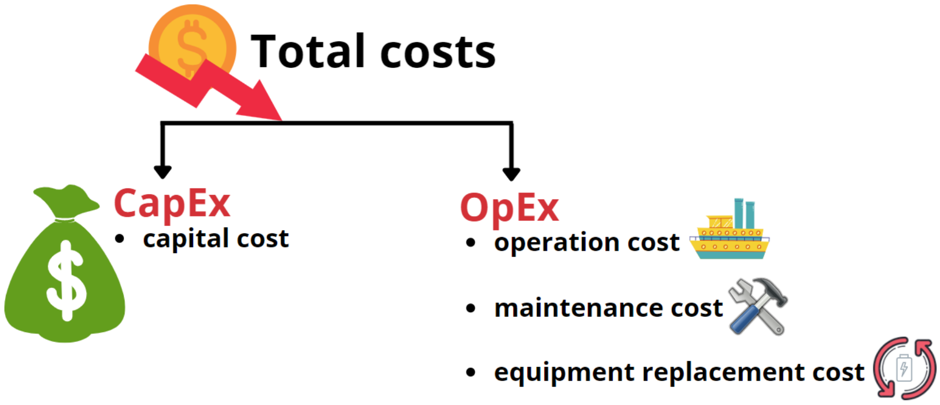

Figure 2. Costs included in the economic analysis

A proper cost comparison can be performed by reducing the total costs to the *NPV*, a measure that discounts the future costs to the present value. With an assumed discount rate (r) of 5%, the *NPV* of each ship power system can be calculated according to the following equation:

$$NPV = CapEx + \sum_{n=1}^{20} \frac{(OpEx_{An})_n}{(1+r)^n}, \tag{7}$$

where $OpEx_{An}$ represents the annual *OpEx* costs and n is the number of years, i.e. lifetime of a ship power system.

2.5. Considered power system configurations

A comparison was made of the fuel cell powering options with the baseline scenario, i.e. a diesel-powered ship, which is currently the most frequently used power system configuration in the Croatian short-sea shipping fleet.

2.5.1. Diesel-powered ship

Before analysing the fuel cell powering options, it should be stated that research into the Croatian short-sea shipping fleet indicated that it consists mainly of outdated ships with an average age of 29 years [50]. According to the national low-carbon development strategy

[63], the transport sector should reduce its GHGs through a set of measures, such as the use of alternative fuels and the application of electric propulsion. Therefore, it is evident that, in the near future, conventional ship power systems should be replaced with alternatives.

2.5.1.1. The LCA of a diesel-powered ship

The environmental performance of a conventional diesel power systems was analysed by performing an LCA for each considered ship. The processes included in the analysis are the diesel engine manufacturing process, the processes of the WTP phase (crude oil recovery, its transportation to the refinery, diesel refining, and its distribution to the pump), and the process of combustion of diesel in the engine, Figure 3.

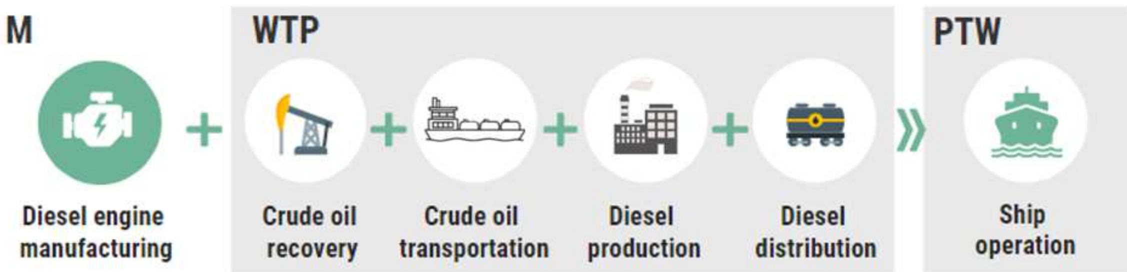

Figure 3. Processes included in the LCA of a diesel-powered ship

The feedstock for diesel production is crude oil, which, in the case of Croatia, is mostly imported from the Middle East. It is assumed that the crude oil is transported by tank trucks about 500 km from the recovery plant and exploitation site to the harbour from where the crude oil is transported via tanker (4,000 km) to the Croatian refinery, which is situated near the tanker terminal. The stationary process of diesel production, as well as the process of crude oil recovery, is obtained from the GREET 2020 database. After the diesel is produced, it is transported via a tank truck up to the corresponding refueling station. The distance of the diesel distribution process differs with the investigated ships. The distance for Ship 1 is equal to 100 km, while for Ship 2 it is 450 km, and for Ship 3 it is 350 km.

The PTW phase refers to the use of diesel for the ship's operation. The fuel consumption per distance, FC_D (kg/nm), of a ship is calculated by multiplying EC_D with the specific fuel consumption SFC_D (kg/kWh), such as in the following equation:

$$FC_D = EC_D \cdot SFC_D. \quad (8)$$

For high-speed diesel engines, the SFC_D is assumed to be 0.215 kg/kWh [64]. As a consequence of diesel combustion, emissions are released, E_{PTW} (kg/nm), and their amount is calculated by multiplying the FC_D with the emission factors, EF (kg emission/kg fuel), for a particular emission i (SO_X, NO_X, CO_2, CH_4, etc.):

$$E_{PTW,i} = FC_D \cdot EF_i. \tag{9}$$

The emission factors for diesel are obtained from [65].

The energy consumed and the released emissions during the process of manufacturing a diesel engine are included in the M phase. By considering the weight ratios of the materials contained in the diesel engine, as proposed in a study by Jeong et al. [66], the environmental performance of manufacturing the given engine is investigated. The weight of a particular material is calculated by multiplying the material's weight ratio with the weight of the engine and serves as an input into the GREET 2020 software. The weight of the engine, m (t), is calculated with the following relation [66]:

$$m = \frac{2 \cdot P_{ave}}{450}. \tag{10}$$

The overall emission, E_i (kg), of the entire power system during the lifetime of 20 years is calculated with the following equation:

$$E_i = LM \cdot (E_{WTP,i} + E_{PTW,i} + E_{M,i}), \tag{11}$$

where E_{WTP} (kg/nm) and E_M (kg/nm) are emissions i released during the WTP phase and the M phase. The calculated emissions are then used for the KPI calculation, and the energy consumed is obtained directly from the software.

2.5.1.2. The LCCA of a diesel-powered ship

The investment cost included in the *CapEx* of a diesel-powered ship refers to the purchase of a new engine, which is calculated by multiplying the average ship power with the assumed conversion factor of 250 €/kW [49].

The engine replacement is not considered due to the assumption that its lifetime is 20 years. Therefore, in the *OpEx* of a diesel-powered ship, the maintenance cost is calculated by multiplying the lifetime energy consumption with the conversion factor of 0.014 €/kWh [67], while the fuel cost is calculated by multiplying the lifetime fuel consumption with the Croatian diesel price of 0.78 €/kg [68].

2.5.2. Fuel-cell-powered ship

2.5.2.1. SOFC-powered ship

An SOFC consists of porous electrodes and a solid electrolyte, i.e. ceramics used as oxygen ion-conducting material. Oxygen (from the air) is fed from an external source into the fuel cell, where it is then reduced on the cathode to oxygen ions which are transported via an electrolyte to the anode. Hydrogen is then oxidized on the anode, resulting in electrons, and electricity is provided to the electric engine [69], [70].

Based on the geometry, an SOFC can be in planar or tubular form. Even though a tubular SOFC is more stable than a planar SOFC, the planar form is preferable due to the higher energy density and easier production [71]. In comparison to other fuel cell types, an SOFC is very flexible regarding fuel, and it offers high efficiency of around 65% in stand-alone operation, and even 70% when combined with gas or steam turbines [72]. However, due to the slow start-up, the integration of another power source, such as a battery, in an SOFC power system is very common [73]. The observed SOFC system is presented in Figure 4, and it is obtained from the study by Kim et al [74]. The battery is placed in the system depending on the way the operating temperature of the system is achieved, which is thoroughly discussed in subsection 2.5.2.3.

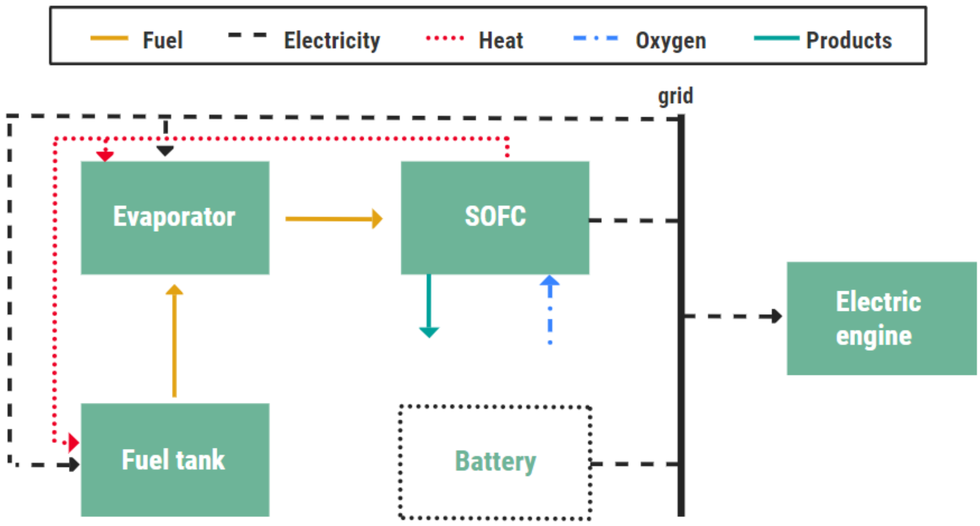

Figure 4. Onboard SOFC power system

According to Figure 4, the liquid fuel enters the evaporator where it is converted into gaseous fuel, which is then fed to the fuel cell. Due to high operating temperature, when entering the fuel cell, the hydrogen carriers are immediately decomposed into hydrogen and other compounds. In this particular case, the thermal decomposition of ammonia into nitrogen and hydrogen occurs in the fuel cell, where hydrogen then oxidizes into water [33]. Another product that can be formed in a fuel cell is NO_X. However, by using an iron-based catalyst for the fast decomposition of ammonia, the formation of NO_X is negligible [75].

Due to the additional load of the equipment, the average power of the ship is increased by 10%, $P_{ave,SOFC}$ (kW), which is equal to the required power of a fuel cell, P_{SOFC} (kW). The fuel consumption of hydrogen and ammonia in an SOFC, i.e. $FC_{SOFC\text{-}H}$ (kg/nm) and $FC_{SOFC\text{-}A}$ (kg/nm), is calculated with the following equation:

$$FC_{SOFC-H} = \frac{EC_{SOFC}}{\eta_{SOFC} \cdot NCV_H}, \tag{12}$$

$$FC_{SOFC-A} = \frac{EC_{SOFC}}{\eta_{SOFC} \cdot NCV_H \cdot x_H}, \tag{13}$$

where η_{SOFC} refers to the fuel cell's efficiency, i.e. 65%, *NCV* represents the net calorific value of a fuel, x_H refers to the hydrogen content in ammonia, i.e. 17.8% [74], while EC_{SOFC} (kWh/nm) refers to the energy consumption of an SOFC-powered ship calculated by dividing the $P_{ave,SOFC}$ with the average speed. The *NCV* for hydrogen is equal to 33.33 kWh/kg (NCV_H) [76].

Various manufacturers guarantee different values of the lifetime of an SOFC, varying from 5,000h to 20,000 h [17]. Assuming that the further development of fuel cell technology will achieve a lifetime even greater than 20,000 h, this upper limit value is taken as the considered lifetime.

2.5.2.2. PEMFC-powered ship

A PEMFC is the most commercialized fuel cell, which is available in many applications, including in the maritime sector. It can reach an efficiency of 50-60%, but its main drawback is its intolerance to impurities and the requirement for pure hydrogen [71]. It contains a proton-conductive polymer electrolyte membrane placed between electrodes. Pure hydrogen as a fuel and oxygen are engaged in electrochemical reactions. The hydrogen is oxidized, the formed electrons result in electricity, while the formed protons due to the electrochemical gradient diffuse through the electrolyte up to the cathode. On the cathode, the oxygen is reduced, and its ions react with protons and form water [77]. The onboard PEMFC system fueled with pure hydrogen is presented in Figure 5, while the onboard PEMFC system fueled with ammonia is presented in Figure 6. The battery is placed in the system depending on the way the operating temperature of the system is achieved, which is fully discussed in subsection 2.5.2.3.

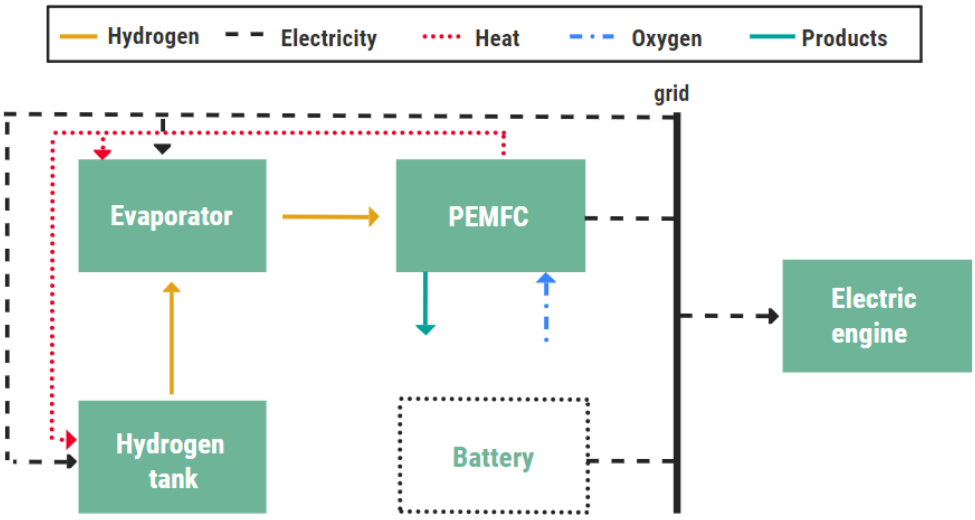

Figure 5. Onboard PEMFC system with pure hydrogen

Ammonia can be used as a fuel in a PEMFC, but its decomposition into hydrogen and nitrogen needs to occur in a separate unit before entering the fuel cell, Figure 6.

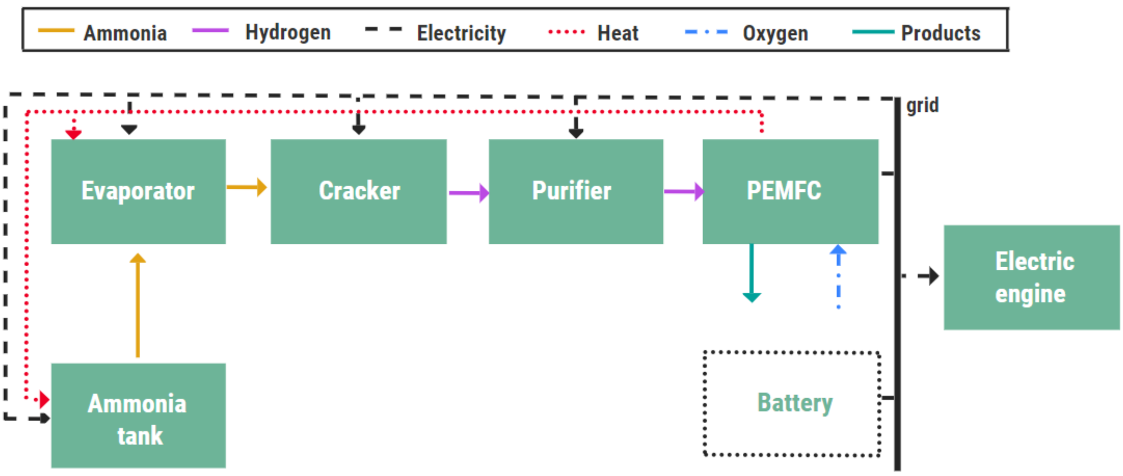

Figure 6. Onboard PEMFC system with ammonia

The required power of a fuel cell is calculated by taking into account that when using hydrogen, P_{ave} is increased by 10%, while when using ammonia, it is increased by 15% due to the additional equipment load. PEMFC power fueled with hydrogen is denoted as $P_{PEMFC\text{-}H}$ (kW), while the power of PEMFC fueled with ammonia is denoted as $P_{PEMFC\text{-}A}$ (kW). While the fuel consumption of a hydrogen-powered fuel cell, $FC_{PEMFC\text{-}H}$ (kg/nm), is calculated with eq. (12), the fuel consumption of an ammonia-powered fuel cell, $FC_{PEMFC\text{-}A}$ (kg/nm), is calculated as follows, by taking into account the efficiencies of the cracker (η_C) (80%) and purifier (η_P) (90%) [74]:

$$FC_{PEMFC-A} = \frac{EC_{PEMFC-A}}{\eta_C \cdot \eta_P \cdot \eta_{PEMFC} \cdot NCV_H \cdot x_H}, \tag{14}$$

where η_{PEMFC} represents the efficiency of a PEMFC of 55%, while $EC_{PEMFC\text{-}A}$ (kWh/nm) refers to the energy consumption of a PEMFC-powered ship fueled with ammonia.

Despite all the advantages, the high costs and durability of a PEMFC are limiting factors for wider deployment. As reported a few years ago, the lifetime of a mobile PEMFC for automobiles was around 3,000 h, while a stationary PEMFC was around 30,000 h. The major reason for the increased degradation is the use of air and not pure oxygen as an oxidant [78]. However, due to the significant development of fuel cell systems, some recent studies have reported a lifetime of 10,000 h and even 20,000 h for a PEMFC operating onboard ship [17]. Assuming that the further development of fuel cell technology will extend its lifetime, this upper limit value is taken as the considered lifetime.

2.5.2.3. Reaching the operating temperature of a fuel cell system

One of the important characteristics of the operation of a fuel cell system, especially for transportation, is its start-up period, i.e. the time of reaching the operating temperature of the fuel cell system to start the process of electricity generation [78]. In this paper, two solutions of reaching the operating temperature of a fuel cell system are investigated, which differ by the way the energy is used for heating the fuel cell system (heating the fuel cell, fuel tank, evaporator, cracker and purifier):

a) Heating the system with shore power while the ship is at berth,
b) Heating the system onboard while the ship is operating, and a battery covers all the energy needs during the start-up period, Figure 7.

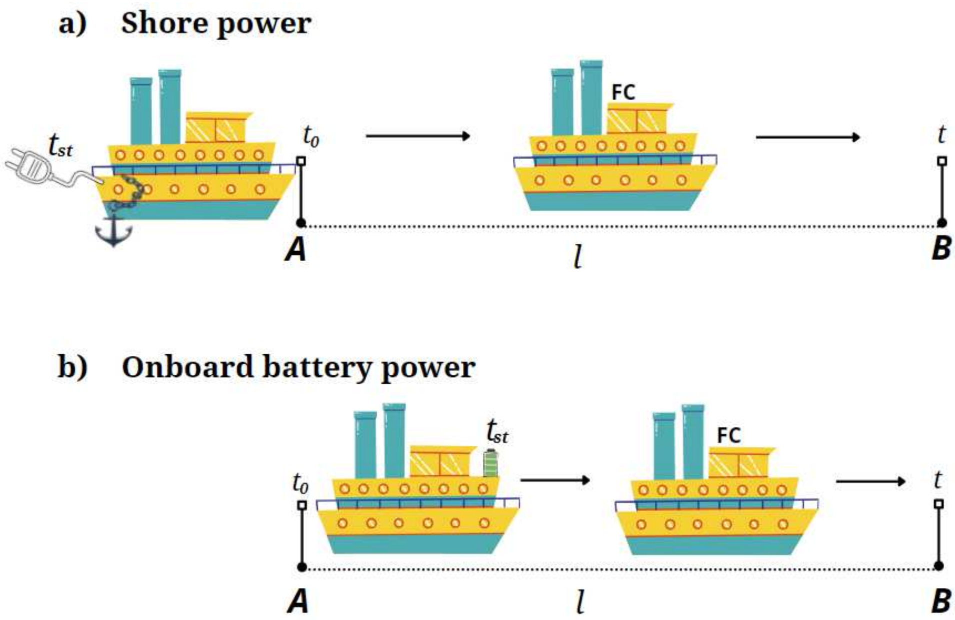

Figure 7. Considered options for reaching the operating temperature of a fuel cell system

The first option considers the heating up of the fuel cell system with shore electricity while the ship is at berth in a port. After the operating temperature is reached and the production of electricity starts, the ship leaves. This option depends on the ship's schedule, which is especially important for a ship powered by an SOFC which has a high operating temperature and requires a start-up period of around 30 minutes [78]. However, due to the ship's busy schedule, after the trip, the fuel cell system will not be fully cooled by the next departure. Therefore, the average start-up period of 20 minutes (t_{st}) is used in the analysis.

Unlike an SOFC, a PEMFC reaches its operating temperature and starts the process of electricity generation in a matter of seconds to minutes [77]. In this paper, it is assumed that within 3 minutes, the operating temperature of the system is reached by heating the system using shore power. When a PEMFC is fueled with ammonia, the required energy for heating the system, $EH_{PEMFC\text{-}A}$ (kWh), is calculated by multiplying the energy demand for starting up the system, i.e. 0.019 kWh/kW [74], with the power of the fuel cell, $P_{PEMFC\text{-}A}$ (kW):

$$EH_{PEMFC-A} = 0.019 \cdot P_{PEMFC-A}. \quad (15)$$

However, when using hydrogen as fuel, the energy required for heating the system is lower due to the absence of a cracker and purifier. Therefore, for a PEMFC fueled with hydrogen, the energy demand for starting up the system is assumed to be 0.015 kWh/kW, and the required energy for heating the system, $EH_{PEMFC\text{-}H}$ (kWh), is calculated according to the following equation:

$$EH_{PEMFC-H} = 0.015 \cdot P_{PEMFC-H}. \tag{16}$$

Since the start-up period of an SOFC is 6.7 times longer than that of a PEMFC, it is assumed that the energy demand for starting up the SOFC system is also 6.7 times greater than the energy demand of the PEMFC system. The energy for heating the SOFC system, EH_{SOFC} (kWh), is calculated as follows:

$$EH_{SOFC} = 0.015 \cdot 6.7 \cdot P_{SOFC}. \tag{17}$$

The second considered solution for reaching the operating temperature of the fuel cell is to incorporate a battery into the ship power system. The battery handles the base loads of the thermal and electric energy demand of a system and also powers the ship until the fuel cell is ready to operate. The battery capacity needs to be sufficient to ensure navigation in that start-up period. Battery capacity, BC (kWh), is calculated according to the following equation:

$$BC = 1.5 \cdot (P_{ave,FC} \cdot t_{st} + EH_{FC}), \tag{18}$$

where EH_{FC} (kWh) refers to the power for heating a fuel cell system and, depending on the type of fuel cell and the fuel used, it is calculated with equations (15)-(17). The battery capacity is increased by 50% for safety reasons and to maintain the state of charge.

The lifetime mileage of a ship powered by a fuel cell, LM_{FC} (nm), is calculated as follows:

$$LM_{FC} = LM - LM_B, \tag{19}$$

where LM_B (nm) refers to the lifetime mileage of a ship powered by a battery, calculated according to the following equation:

$$LM_B = \left(\frac{t_{st}}{t}\right) \cdot LM, \tag{20}$$

where t (h) represents the duration of the entire trip.

2.5.2.4. The LCA of a fuel-cell-powered ship

Since hydrogen represents an ideal fuel for onboard fuel cells, the environmental performance of three different types of hydrogen is investigated. Grey and blue hydrogen are produced from natural gas, while green hydrogen is produced by RESs through the process of electrolysis. The processes included in the LCA are presented in Figure 8.

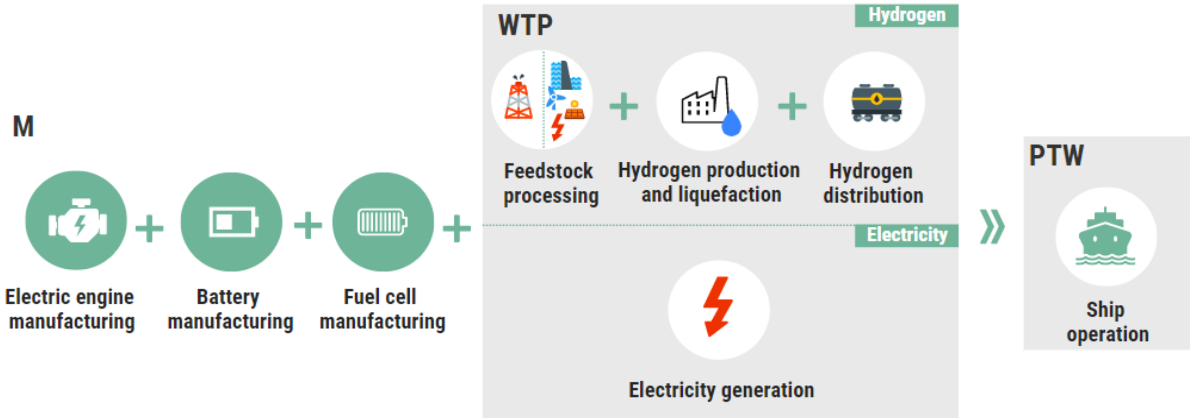

Figure 8. The processes included in the LCA of a hydrogen-powered ship

Feedstock processing for grey and blue hydrogen refers to the process of natural gas recovery, while for green hydrogen it refers to the electricity generation by solar, wind, and hydro energy. These stationary processes are obtained from the GREET 2020 database, while the transportation processes are modified. Since Croatia currently does not have a developed hydrogen market or production facilities, it is assumed that each type of hydrogen is produced in Western Europe, liquefied and transported to Croatia via tank trucks over a particular distance (Ship 1: 1,100 km; Ship 2: 1,450 km; Ship 3: 1,350 km).

In this paper, ammonia is considered as a potential hydrogen carrier for onboard fuel cells. The processes included in the LCA of an ammonia-powered ship are shown in Figure 9. The WTP phase involves feedstock processing, i.e. natural gas recovery or electricity generation from RESs, the production of grey, blue and green ammonia, and fuel distribution to the refueling station. It is assumed that the transportation process of ammonia is the same as for the transportation process of hydrogen.

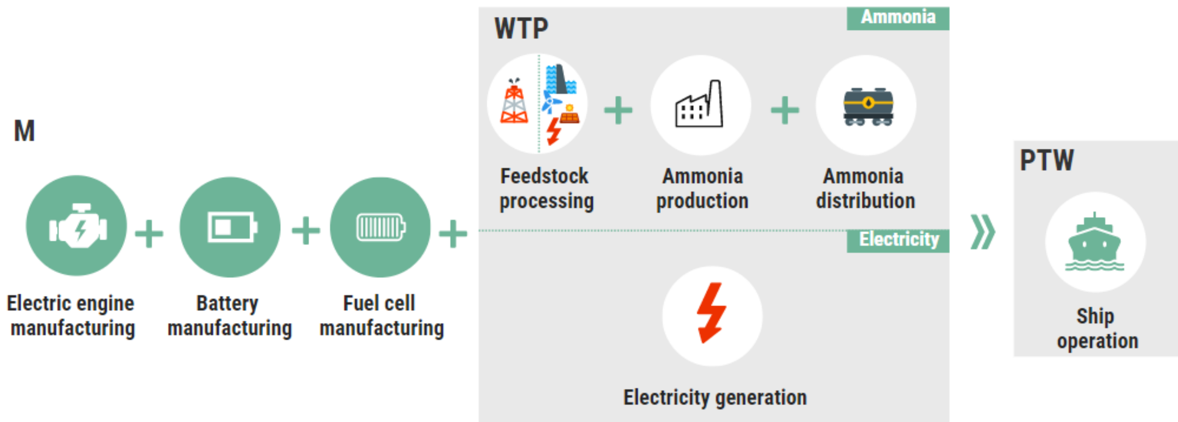

Figure 9. The processes included in the LCA of an ammonia-powered ship

Electricity is used during the start-up of the fuel cells. Therefore, each LCA of the fuel cell power system configuration also includes the electricity generation process within the WTP phase. In this analysis, the European electricity mix from the GREET 2020 database is used, Figure 10.

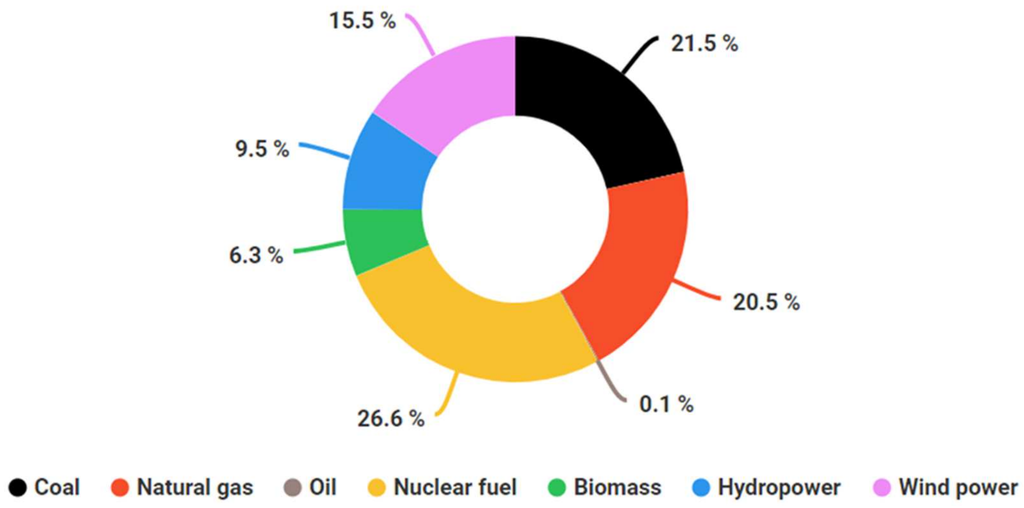

Figure 10. The European electricity mix obtained from the GREET 2020 database [61]

The M phase of each considered fuel cell configuration considers the manufacturing of the electric engine, the fuel cell, and the battery. While the environmental impact of an electric engine is calculated in the same way as for the diesel engine, the released emissions and energy consumed during the battery manufacturing process is obtained from the GREET 2020 database, where the only input is the weight of the battery. A Li-ion battery with nickel manganese cobalt oxide chemistry is considered, and its weight is calculated by dividing the required battery capacity with the energy density of 0.22 kWh/kg [80]. After the battery lifetime of 9,000 cycles of charging and discharging, the battery is replaced with a new one and is accounted for in the assessment. The environmental impact of a fuel cell is described by using the weights of materials used for manufacturing the SOFC [81] and the PEMFC [82]. Their replacement is considered by taking into account their operating hours.

The overall emissions are calculated with eq. (11) and their values are incorporated in the methodology for the KPI calculation. The energy consumed is obtained directly from the GREET 2020 software [61].

2.5.2.5. The LCCA of a fuel cell-powered ship

The economic analysis over the lifetime of a fuel cell power system is performed through LCCA, where the *CapEx* and *OpEx* are calculated. The prices for particular equipment and fuel are presented in Table 2.

Table 2. The considered prices for the economic analysis of a fuel cell-powered ship

Investment	Fuel cell	SOFC (€/kW)	2,200-7,670 [74], [83], [84]
		PEMFC (€/kW)	420-840 [74], [47], [48]
	Battery (€/kWh)		200 [85]
Fuel	Grey hydrogen (€/kg)		3.3 [86], [87], [88]
	Blue hydrogen (€/kg)		3.88
	Green hydrogen (€/kg)		5.8[86], [87], [88]
	Grey ammonia (€/kg)		0.31 [89]
	Blue ammonia (€/kg)		0.43
	Green ammonia (€/kg)		0.62
	Electricity (€/kWh)		0.078 [68]

The *CapEx* includes the investment cost of a battery and a fuel cell with the additional appropriate equipment, i.e. an electric motor, evaporator, etc. The investment cost of a battery is calculated by multiplying the required *BC* by its price. The investment cost of a particular fuel cell is calculated by multiplying its cost by its power. While various studies represent different prices presented in Table 2, it is assumed that the further development of fuel cell technology will result in lower prices. Therefore, the lower limit of the range is used as the fuel cell price. The liquid hydrogen storage cost is calculated by multiplying the amount of hydrogen required for the ship operation (during a round trip) with the NCV_H and liquid hydrogen storage price of 5 €/kWh. The required mass of hydrogen is increased by 20% for safety reasons [90]. The additional equipment is incorporated in the capital cost by increasing the cost of a fuel cell by 20% for an SOFC-powered ship fueled with either ammonia or hydrogen and a PEMFC-powered ship fueled with hydrogen. In order to take into account the required cracker and purifier for a PEMFC-powered ship fueled with ammonia, the investment cost of a fuel cell is increased by 30%.

The fuel costs include the costs of electricity, ammonia and hydrogen, whose prices are presented in Table 2. Whether the fuel cell is heated from the shore or during the ship operation, the overall cost of the electricity is calculated by multiplying its price for Croatian medium-size industry by the consumed electric energy. The European production costs of grey and green hydrogen are obtained from [86], and they are 1.5 €/kg for grey hydrogen and

2.5-5.5 €/kg for green hydrogen. To obtain the full price, the liquefaction cost of 0.9 €/kg, [87] and distribution costs of 0.9 €/kg, [88] are added to the average production price of grey and green hydrogen. Their final price for the Croatian case is 3.3 €/kg for grey hydrogen and 5.8 €/kg for green hydrogen. The global price of grey ammonia of 0.31 €/kg is obtained from a study by Hansson et al. [89]. However, the price of green ammonia is very different in the literature, mainly due to the cost of electricity and hydrogen required for its production [91], [92]. Since several studies predict that in 2040 the price of green ammonia will be less than 0.31 €/kg [93], [94], in this paper the price of green ammonia is assumed to be twice that of grey ammonia, i.e. 0.62 €/kg. Due to the lack of literature data on the prices of blue hydrogen and blue ammonia, they are calculated by increasing the grey hydrogen/ammonia price by the CCS cost, i.e. 60-90 €/ton of CO_2. Bearing in mind the prediction that the CCS cost in the early 2020s will be lower than 50 €/ton of CO_2 [95], the lower limit of the range is taken into account. According to the GREET 2020 database, the amount of CO_2 emissions released during the production of grey hydrogen is 10.7 kg per kg of hydrogen, while during the production of grey ammonia, 2.29 kg CO_2/kg ammonia is released. By considering that at least 90% is captured and stored, the CCS amounts to 0.58 € per kg of produced hydrogen and 0.12 € per kg of produced ammonia.

Besides fuel cost, within the *OpEx*, the maintenance and equipment (battery and fuel cell) replacement costs are included. While the lifetime maintenance cost of a power system refers to 10% of *CapEx*, the replacement cost takes into account the investment cost of the battery and fuel cell. However, it is assumed that their prices will decline by at least 25% by the time they need to be replaced, which represents their replacement cost.

2.6. Assumptions and limitations

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

- The system boundary is fixed to the ship power systems. Hence, the environmental and economic KPIs are investigated through the emissions, energy consumed, and costs related only to the ship power system, while other units of the ship (e.g. the hull, additional equipment, crew, port operations, etc.) are not considered. However, this approach is sufficiently accurate to identify the technical solutions that result in emission reduction at a reasonable price, compared to the configuration of a conventional diesel power system.

- Within the LCA, the fuel distribution processes and the transportation of the raw material to the production facility are simplified. However, since the stationary processes make major contributions to overall WTP emissions, a change in the distribution and transportation pathways would not have a major impact on those emissions.
- The environmental impacts of the considered fuel cells are investigated based on the environmental footprints of the materials used in the process of their manufacture. However, data for some materials used in the manufacturing process of an SOFC and PEMFC are not available in the GREET 2020 database. Although some materials are omitted, the environmental assessment is still accurate since the M phase represents a minor contributor to overall emissions compared to the WTP phase.
- Further development of fuel cell technology will result in lower prices and in the better performance of fuel cells. Hence, in this paper, the considered lifetimes of fuel cells are taken as an upper limit value from the lifetime ranges obtained from the literature, while the considered costs of the fuel cells are the lowest among those found in the literature.
- The investment cost of additional equipment for the fuel cell system (e.g. cracker, purifier, etc.) are approximated. Since the investment cost of a fuel cell system is relatively minor compared to the fuel costs of the system, this approximation does not have a major influence on the final results.
- Short-term fluctuations of future fuel prices are not considered, and therefore the cost assessments follow the business-as-usual scenario. The only exception is the assumption that fuel cell prices and the battery price will decline by at least 25% by the time they will need to be replaced. The effect of diesel, green hydrogen and green ammonia fuel costs on the profitability of different power system configurations is presented in the analysis within the discussion section.

3. Results and discussion

The LCA and LCCA results of the implementation of different fuel cells and fuels are presented in Figure 11 and Figure 12. These results are used to select the best environmental and economical options for the fuel cell system on three ships for coastal navigation. The selected options are then compared with the diesel power system based on the calculated KPIs. In the following results, Gy-H denotes grey hydrogen, B-H denotes blue hydrogen, Gn-H refers to green hydrogen, Gy-A represents grey ammonia, B-A refers to blue ammonia, while Gn-A denotes green ammonia.

In this paper, two ways of reaching the temperature of the fuel cell system are considered, i.e. heating the system with shore power when the ship is at berth (onshore), or heating the system with battery power while the ship is operating (onboard). However, heating the SOFC onboard Ship 1 (SOFC-onboard) is not considered since the duration of a one-way trip of the ship is shorter than the start-up period of an SOFC.

In the first step, the LCA results are used to highlight the most ecological use of a fuel cell with a certain fuel. Although other emissions are also analysed for different fuel cell systems, the emphasis is on the decarbonization of the shipping sector. Based on the LCA results, Figure 11, green hydrogen is indicated as the most environmentally friendly fuel solution from the global warming point of view, and it results in the lowest life-cycle CO_2-eq emissions.

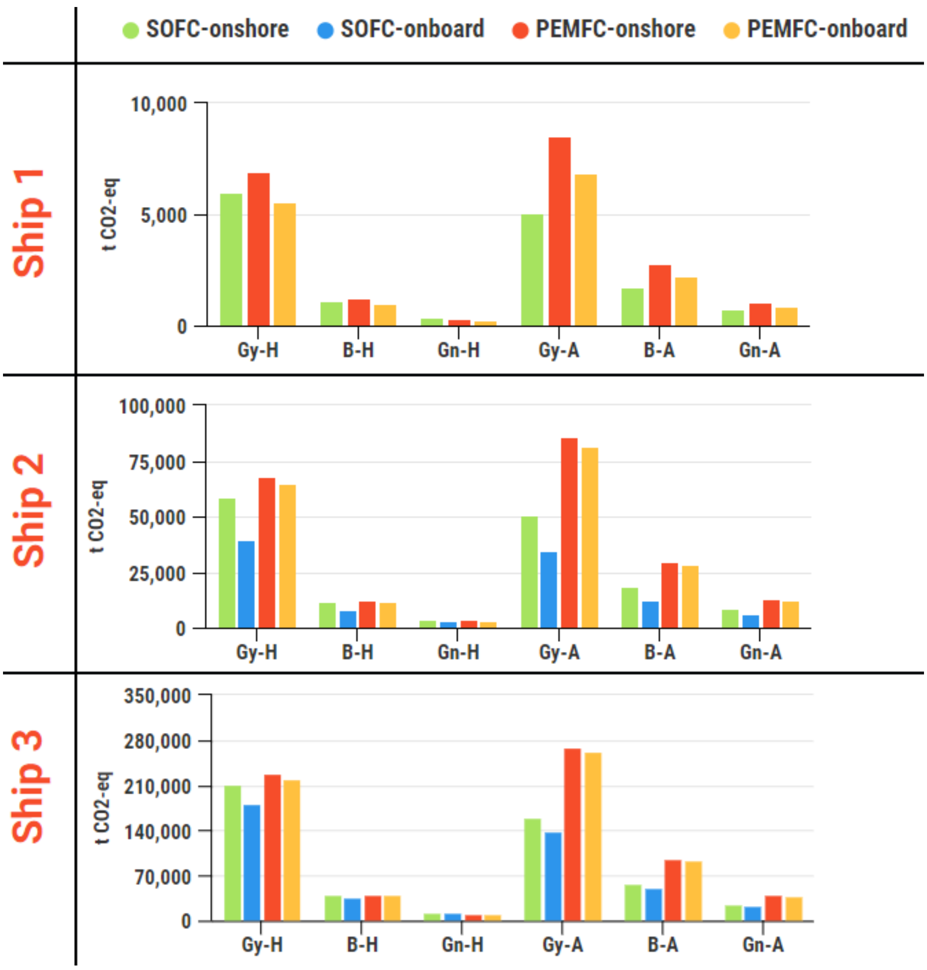

Figure 11. Life-cycle CO_2-eq emissions

The LCA comparison of the analysed power system indicates that heating the fuel cell system onshore results in higher life-cycle CO_2-eq emissions compared to the power system configuration when the fuel cell is heated onboard. The greatest impact of heating SOFC onboard on reducing emissions can be seen in the case of Ship 2. Due to the slow start-up period of an SOFC, Ship 2 is powered by a battery for around 2/3 of its route, while Ship 3 is powered by a battery for around 1/7 of its route. Therefore, the onboard heating of the SOFC on Ship 2 resulted in 33% lower CO_2-eq emissions than onshore heating, while for Ship 3, this reduction of emissions is around 14%.

Regarding the particular fuel cell, the use of an SOFC is an environmentally friendlier solution than the use of a PEMFC. The analysis indicates that the combination of grey hydrogen for an SOFC has the highest emissions among the considered fuels for an SOFC. However, when observing all the considered fuel cell types and different fuels, the grey ammonia used in a PEMFC, heated onshore, has the highest contribution to global warming. This is mainly due to the lower efficiency of the PEMFC compared to the efficiency of an SOFC, but also due to the PEMFC's requirement for pure hydrogen. The ammonia is firstly decomposed into hydrogen and nitrogen in a cracker, and then this hydrogen is purified in the purifier. By taking into account the losses in that equipment, the fuel consumption of ammonia is higher than it is for an SOFC system. Since grey ammonia is produced from natural gas in a process that is energy-intensive, the higher consumption of ammonia results in higher overall emissions.

The options that are nearly as environmentally friendly as the green hydrogen power system configuration are power systems with blue hydrogen and green ammonia as a fuel, especially for an SOFC-powered ship. Before the selected solutions are compared with the performance of a diesel-powered ship, the LCCA results, Figure 12, are observed to conclude which option has the potential to reduce emissions but is at the same time economical.

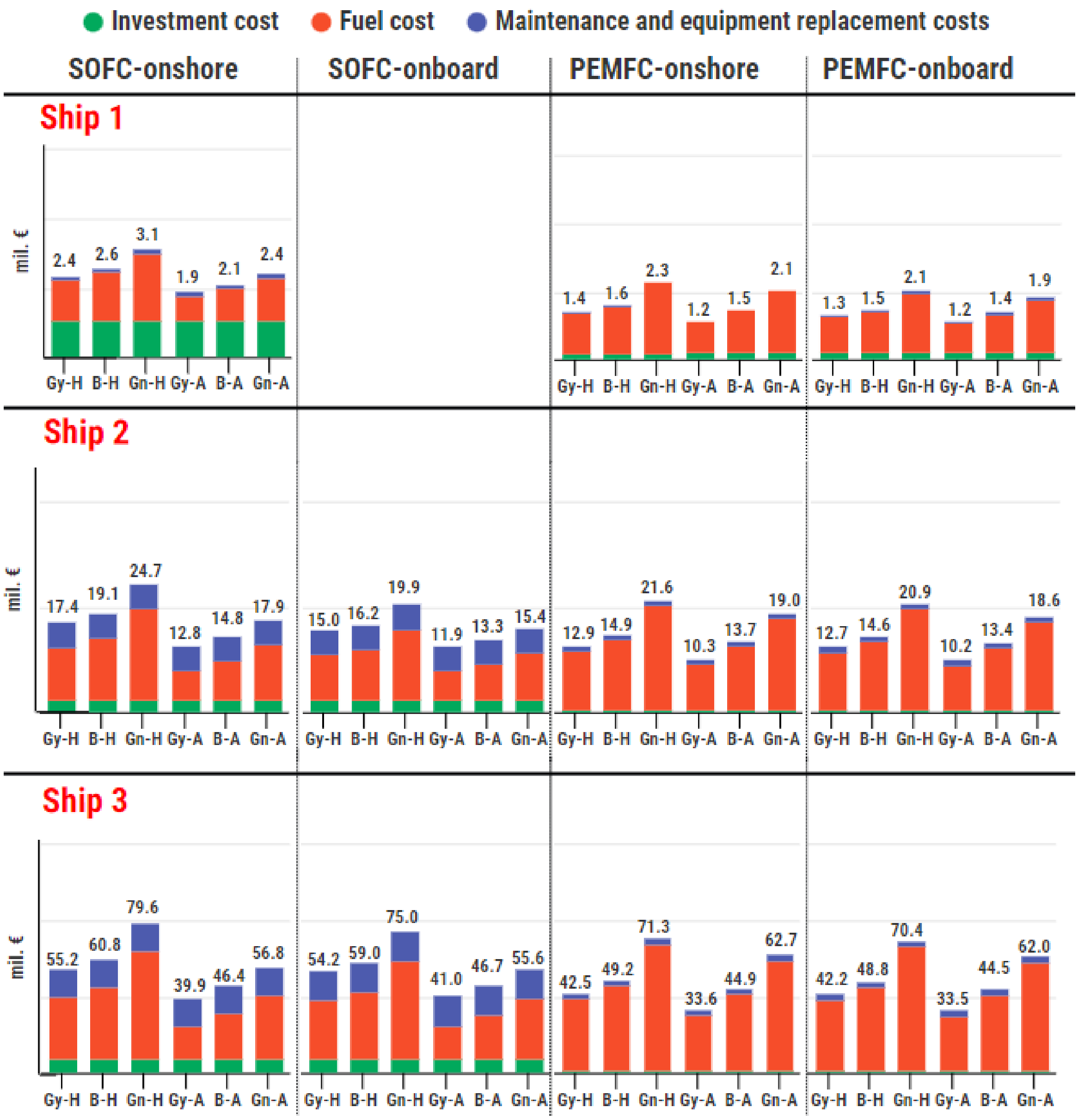

Figure 12. The LCCA results of the considered fuel cell systems

The LCCA comparison of PEMFCs and SOFCs for each considered ship indicates that the SOFC system implemented onboard results in higher costs than the PEMFC system. Even though the SOFC has higher efficiency than the PEMFC, and so requires less fuel for electricity generation, the capital cost of the SOFC system is higher than the capital costs of the PEMFC one. Regarding the method of reaching the required temperature for a fuel cell system, onboard heating, that is, when the battery heats the system and powers the ship, is the less expensive solution. This is mainly due to the fact that the electricity cost is far lower than the fuel cost. Exceptions can be observed in the case of Ship 3 and the SOFC powered by grey ammonia and blue ammonia. Regarding the fuel, grey ammonia is the most cost-effective fuel for the fuel cell. However, the LCA indicates high CO_2-q emissions when grey ammonia is used.

Although green hydrogen is the most environmentally friendly fuel that can be used in a fuel-cell-powered ship, the LCCA results show that green hydrogen is the most expensive fuel. The selected options for further comparison with the existing diesel-powered ship (denoted as D) are those whose released emissions and resulting costs are among the lowest of the analysed options, i.e. a fuel-cell-powered ship (onboard heated) with blue ammonia, green ammonia and blue hydrogen as fuels. The results of the comparison are presented in Figure 13.

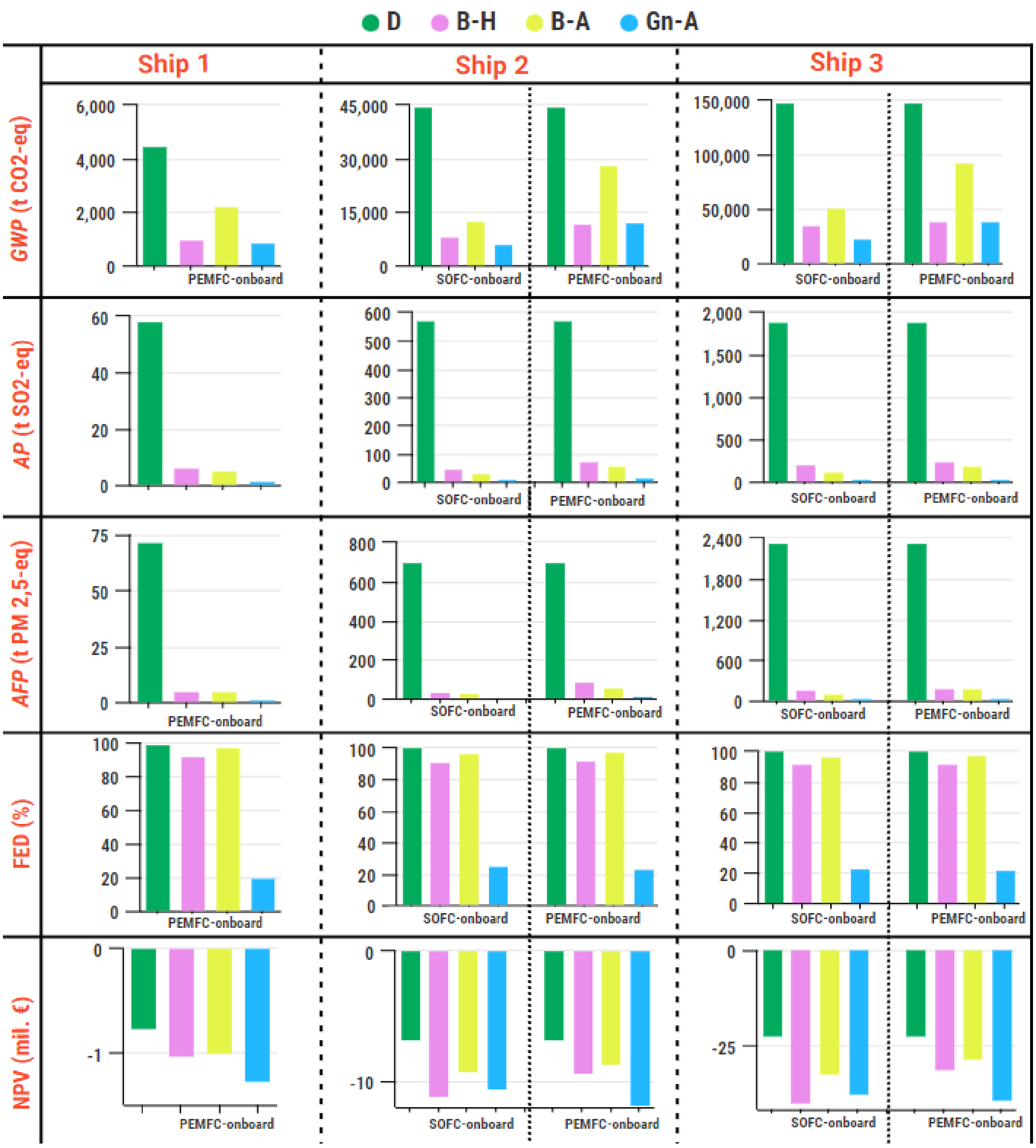

Figure 13. A comparison of the KPIs of different ship power systems

According to the comparison presented in Figure 13, the existing diesel-powered ship has the highest impact on climate change, acidification, human toxicity and depletion of fossil fuel. The results indicate that the fuel with the lowest environmental KPIs is green ammonia, with reductions in *GWP* by 72%-84%, in *AP* and *AFP* by 98%-99%, and in *FED* by 75%-80%, compared to a diesel-powered ship. The environmental KPIs are higher when a PEMFC is used, except in the case of *FED*, when the use of an SOFC results in a slightly higher percentage of fossil energy demand.

Regarding profitability, the diesel power system configuration is the most cost-effective power system. The main reason for this is the low fuel and investment costs compared to fuel cell power systems. The second most cost-effective power system is the blue ammonia-powered ship, which, when compared to a diesel-powered ship, reaches 27%-43% higher *NPV*s, depending on the particular ship and type of fuel cell used. The investment cost of a ship power system with fuel cells mainly refers to the capital cost of a fuel cell. Since various prices of fuel cell stacks can be found in the literature, the sensitivity analysis of the *NPV* of fuel cell options with respect to the fuel cell price was performed. The fuel cell price varies by ± 75%, with an increment of 25%. The results of the analysis are illustrated on Ship 2, fueled by green ammonia.

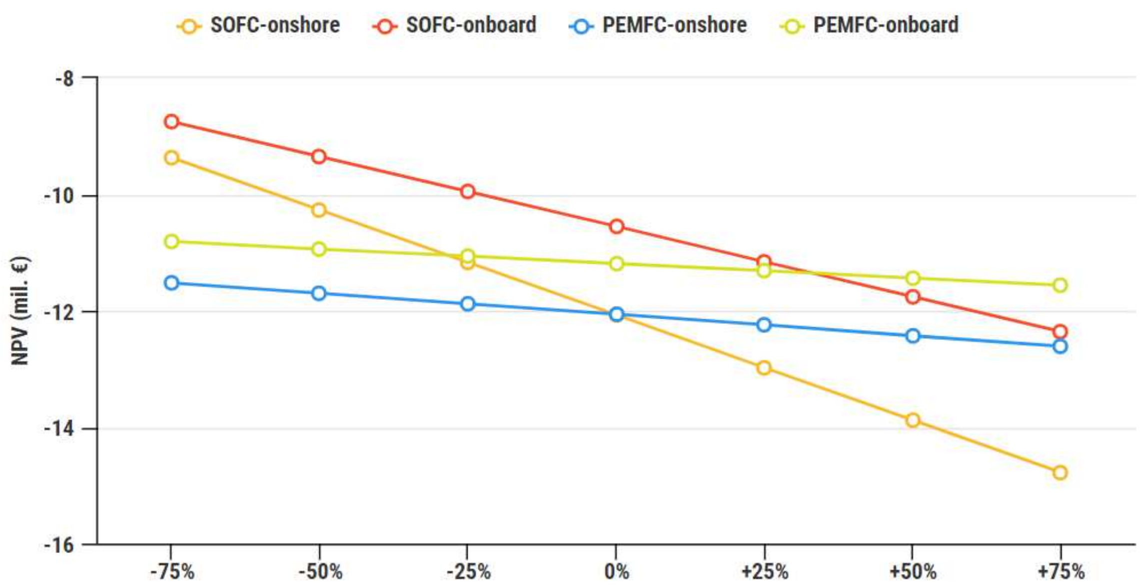

Figure 14. Sensitivity analysis of the *NPV* of different powering options with respect to fuel cell price

The greatest impact of the fuel cell price variations is shown in the case of an SOFC, especially when the SOFC is heated with onshore energy. In this case, due to the longer working hours of the fuel cell than when the SOFC is heated onboard, the fuel cell systems are replaced three times, while for the onboard heating of the SOFC, the maintenance cost refers to the replacement of the fuel cell twice and the replacement of the battery seven times. This results in higher maintenance costs, which, along with higher fuel costs, affects the trendline of SOFC-onshore in Figure 14.

Besides hydrogen and ammonia, use of biofuels, especially biodiesel, in the ship power system is often investigated for the potentially great reduction of CO_2 emissions, given the general opinion that biofuels are carbon-neutral fuels, i.e. it is considered that the CO_2 emissions released during biofuel combustion are absorbed by biomass that will be further used for biofuel production [96]. In order to compare the environmental impact of biodiesel in the ship power system with that of diesel-powered ships and fuel cell options powered by hydrogen and ammonia, an analysis was performed where *GWP* and the total costs were compared. The fuel cell systems are heated on board, while the biodiesel is used as a diesel-biodiesel blend (B20), which contains 80% diesel and 20% biodiesel. The data on the life-cycle CO_2-eq emissions and life-cycle costs of a B20-powered ship are obtained from a study by Perčić et al. [49]. The results of the analysis are illustrated on Ship 2, and they are presented in Figure 15.

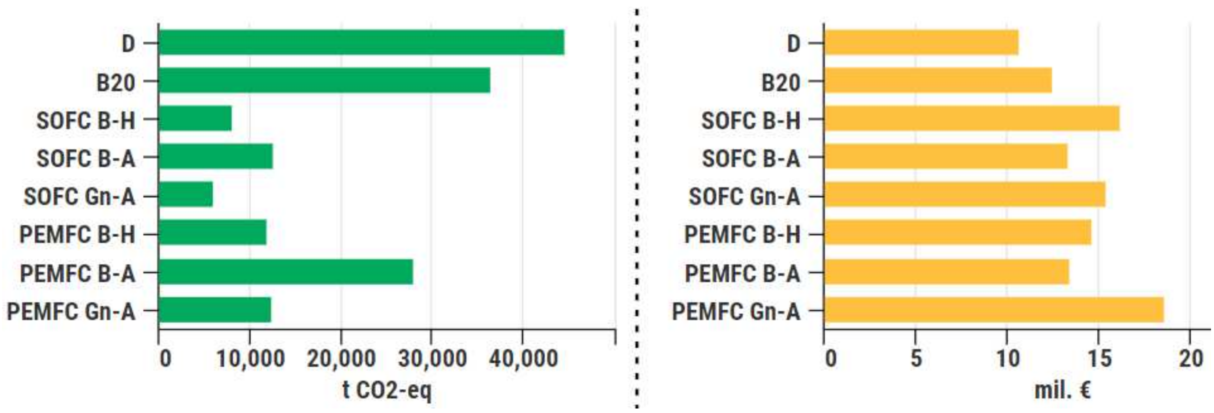

Figure 15. A comparison of the GWP and life-cycle cost of the investigated fuel cell ship power systems, the diesel-powered ship and the B20-powered ship

The biodiesel-diesel blend B20 results in higher emissions than the considered fuel cell options fueled with hydrogen and ammonia, but its life-cycle GHG emissions are still lower than the currently used diesel-power system configuration. Regarding the total costs, the B20-powered ship results in higher costs than the diesel-powered ship, but it represents a cost-effective option compared to the considered fuel cell options. With respect to the decarbonization goal set by IMO, biodiesel used in a blend with a great share of diesel should not be considered as a substantial decarbonization measure.

In summary, the use of green ammonia, blue ammonia and blue hydrogen in fuel cell systems installed onboard ships are highlighted as potential powering options which can be used to replace the diesel-power system. This replacement results in the reduction of GHGs, but it also increases the total costs. These data are summarized in Table 3.

Table 3. Results of the replacement of the diesel-power system with the considered fuel cell systems

	Diesel-powered ship replacement	
	Reduction of *GWP*	Increase of *NPV*
SOFC-onboard Gn-A	84% - 86%	56% - 68%
PEMFC-onboard Gn-A	72% - 80%	65% - 75%
SOFC-onboard B-A	65% - 72%	37% - 43%
PEMFC-onboard B-A	37% - 50%	27% - 29%
SOFC-onboard B-H	76% - 82%	64% - 80%
PEMFC-onboard B-H	73% - 78%	35% - 38%

An incentive for the application of these ship power systems with no tailpipe emissions could be the potential implementation of the carbon tax in the shipping sector. As investigated by Perčić et al. [49], the carbon tax can be observed in three scenarios, where the most rigorous is the Sustainable Development (SD) scenario, which reaches a carbon allowance cost of 115 €/ton of CO_2 by 2040. The carbon tax only refers to the tailpipe CO_2 emissions. By following up the methodology presented in this paper, the total annual CO_2 emissions of the Croatian ro-ro passenger fleet released during the diesel combustion in a ship engine is equal to around 50,000 t. The penalization of these emissions can be achieved with the SD scenario, which would lead to an increase of the *NPV* of existing ships by around 15%. This represents a great incentive towards the application of emission reduction measures. However, when compared to blue-ammonia-powered ships, their *NPV*s are still higher than those of the diesel-powered ship, ranging from 11% higher (Ship 1), 6% higher (Ship 2) and 7% higher (Ship 3) when using a PEMFC, while when using an SOFC, the *NPV*s of Ship 2 and Ship 3 are 15% and 20% higher, respectively.

Green ammonia is highlighted as a viable marine fuel and whose application in a fuel cell would result in achieving the IMO 2050 goal. Although it can be used directly in an

SOFC, ammonia cannot be used directly in a PEMFC due to the potential poisoning of the platinum catalyst and a reduction of the membrane conductivity [96]. Hence, in this paper, the ammonia is firstly decomposed in a cracker, where further hydrogen is purified to eliminate all the impurities that could lead to PEMFC degradation. However, for the direct use of ammonia, the Direct Ammonia Fuel Cell (DAFC) is a promising option. DAFC operates at a moderate temperature, and it is suitable for mobile applications [98]. However, the reaction of ammonia oxidation causes stability issues of the catalyst [99]. The solution for this is the use of an ammonia-based fuel cell with an anion exchange membrane which offers a robust and cost-effective alternative approach by enabling nonprecious electrocatalysts with acceptable performance, durability, and minimized system-level complexity [100], [101].

Interest in green ammonia has risen in recent years, driven by the decarbonization goals of different sectors. Green ammonia represents a viable and economical competitive fuel whose carbon-neutral characteristic offers clean energy. Further development of the production technology of ammonia and a decrease in its price will widen its use in the energy sector [93]. An analysis was performed to gain insight into the influence of future fuel prices on the *NPV* of the investigated power system configurations with sustainable fuels, i.e. green ammonia and green hydrogen, and diesel fuel as a baseline scenario, and the results are illustrated with regard to Ship 2, Figure 16. The projections for diesel and hydrogen prices are presented in a study by Gonçalves Castro et al. [102], from where the trend of decline in the hydrogen price and trend of increase in the diesel price are obtained. Green ammonia's price is forecast to be below 0.31 €/kg, by 2040 [93]. The projections of fuel prices are also represented per m^3 to account for the density of each fuel obtained from [103].

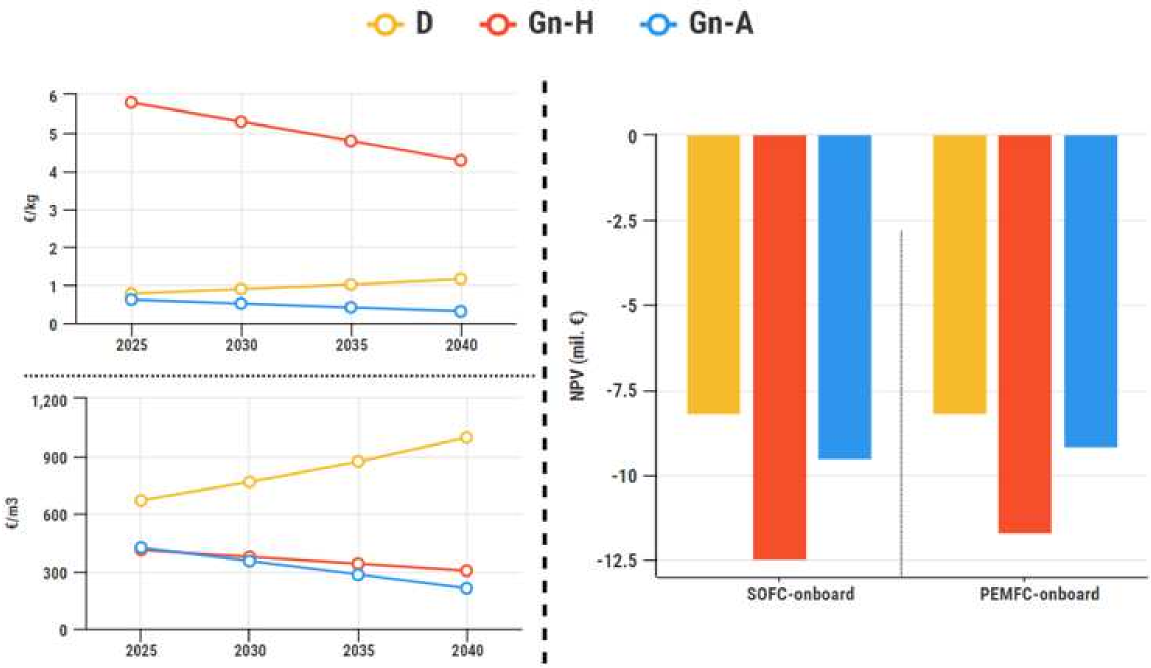

Figure 16. The projections of fuel prices up to 2040 (left) and an analysis of *NPV*s with respect to the forecast of future fuel prices (right)

The analysis indicates that green ammonia in a PEMFC heated onboard represents a promising alternative to diesel-powered ships with a great reduction in air pollutants, the fossil energy consumed, but where the *NPV* is slightly higher (by 12%). A greater impact can be seen in the decrease in the future price of hydrogen and ammonia in the case of a PEMFC-powered ship since its major cost is the fuel cost, and the investment cost is minor compared to the investment cost of an SOFC-powered ship. In comparison to the business-as-usual scenario, the *NPV* of diesel-powered ships increases by 17%, while the *NPV* of a green ammonia-powered ship is reduced by 10% when used in an SOFC and by 22% when used in a PEMFC. Even though the forecast predicts a decline in the price of green hydrogen, it is still an expensive fuel in comparison with green ammonia.

4. Conclusion

Fuel cells represent an innovative technology that could help in decarbonizing the shipping sector. This paper reports on research conducted on different fuel cell types, i.e. a low-temperature fuel cell (PEMFC) and a high-temperature fuel cell (SOFC), used as the powering option of three Croatian ro-ro passenger ships. Hydrogen and ammonia were investigated as fuel for a fuel cell, taking into account their type of production (grey, blue and green types of fuel). Based on the time required for the fuel cell system to heat up, two options were considered: the fuel cell system is heated when the ship is at berth, or the fuel cell system is heated by battery while the ship is operating, where the battery represents the main ship power source during the start-up period. In order to determine which fuel cell and fuels are both environmentally friendly and economical, LCA and LCCA were performed and used to calculate the environmental and economic KPIs. The selected fuels were compared with the existing diesel-powered ship based on their KPIs. The main findings of the research can be summarized as follows:

- The performed LCA indicated that the use of a PEMFC in a ship power system results in higher CO_2-eq emissions than the use of an SOFC onboard. The main reason is the lower efficiency of the PEMFC compared to the SOFC, which results in a higher amount of fuel required for the same amount of electricity output. The higher fuel consumption results in higher emissions.
- Although the LCA showed green hydrogen to be the most environmentally friendly fuel, the LCCA results indicated that the use of that fuel is not cost efficient since it is more expensive than the other considered fuels.
- The total costs of the fuel cell system powered by grey ammonia are the lowest among the considered options. However, this fuel is not considered acceptable for use onboard since its use results in high emissions.
- The LCCA showed that the SOFC power system configuration has higher total costs than the PEMFC power system configuration. Even though the SOFC has higher efficiency and requires less fuel for electricity generation, the capital cost of the SOFC system is higher than the capital costs of the PEMFC one.
- Both the LCA and LCCA results showed that heating the fuel cell system with onshore power results in higher emissions and higher total costs than the option of onboard heating.
- Following the LCA and LCCA results, blue hydrogen, blue ammonia and green ammonia were selected for comparison with a diesel-powered ship. While the diesel power system configuration resulted in the highest environmental KPIs, its economic KPI, i.e. *NPV*, is the lowest among the considered options.
- The implementation of blue ammonia in an SOFC system onboard is highlighted as one of the most feasible solutions, which would result in a great reduction in GHGs of

65%-72%, but at an acceptable cost which is 37%-43% higher than that of a diesel power system. Another feasible solution that offers a great reduction of 73%-78% in GHGs at a cost that is 35-38% higher than a diesel-powered ship is the PEMFC-powered ship fueled with blue hydrogen.

- Although the considered fuel cell systems with different fuels are not economical, the fuel cell system with blue and green fuels (hydrogen and ammonia) satisfy environmental requirements. With the further development of supply chains and an appropriate infrastructure and a reduction of fuel prices, the fuel-cell-powered ship will become feasible. An analysis was performed with respect to the forecast of the future prices of sustainable fuels (green ammonia and green hydrogen) compared to diesel. The results indicate that the application of green ammonia in a PEMFC for maritime purposes would seem to be feasible after 2040, but green hydrogen will probably remain expensive compared to green ammonia.

Finally, although the research focuses on the case study of Croatia, the developed models for the application of SOFCs and PEMFCs onboard ships and models for the heating of the fuel cell system are generally applicable to other short-sea shipping sectors of other countries if a set of specific input data is available.

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