Energy Conversion and Management: X 22 (2024) 100539

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Ammonia-powered ships: Concept design and feasibility assessment of powertrain systems for a sustainable approach in maritime industry

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ARTICLE INFO

Keywords:
Hydrogen carriers
Ammonia
Zero-emission vessels
Maritime industry
Shipping decarbonization

ABSTRACT

The decarbonization of the shipping industry is pushing towards the introduction of low-carbon fuels such as hydrogen carriers and towards the installation of cleaner propulsion systems. Among different hydrogen carriers, ammonia (NH_3) is considered a promising option due to its high volumetric energy density and to its easier storage and transportation in comparison with pure hydrogen. Therefore, this study is focused on the design, modeling, and feasibility assessment of ammonia-based propulsion systems for shipping applications. Two NH_3-based fuel cell power generation systems are analyzed: i) a NH_3-based Proton exchange membrane Fuel Cell (PEMFC) system and ii) a NH_3-based Solid Oxide Fuel Cell (SOFC) system. These systems are designed to replace a conventional diesel powertrain installed on board a container ship. The fuel consumption, according to the ship load profile, is calculated and the analysis on the masses and volumes of the fuel storage tanks and of the ammonia powertrain systems is performed. Results highlight that on board installation of the proposed ammonia-based propulsion technologies causes greater masses and volumes with respect to the conventional diesel system. This criticality, in the face of an advantage in terms of avoided CO_2 emissions per cruise, could be overcome by accepting a cargo capacity reduction. It is estimated a cargo reduction in the range 3.3% – 4.8% for the proposed fuel cell-based powertrain solutions. However, by valorizing the avoided CO_2 emissions, it is possible to recover the economic penalty due the cargo reduction and break-even with the reference diesel scenario.

Introduction

Shipping accounts for 80–90 % of global trade, moving every year over 10 billion tons of solid and liquid bulk cargo across the ocean all over the world [1,2]. Currently, the world trade percentage is increased by about 18 % compared to 2016, and this trend is expected to increase up to 50 % by 2040 [3]. The use of fossil fuels, such as Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO) is predominant in the maritime sector [4]. This implies that, as trade by sea increases, greenhouse gases emissions (GHG) due to the use of fossil fuels will significantly increase [5]. GHG emissions growth from 1990 is foreseen to range from 50 % to 250 % by 2050 if more stringent policies and mitigation measures will be not adopted [6,7]. In order to reduce pollution in maritime sector, the International Convention for the Prevention of Pollution from Ships (MARPOL) has prohibited ships using HFO in ports [8]. In 2018, the International Maritime Organization (IMO) adopted an initial strategy aimed to reduce the GHGs emissions from seagoing ships, setting out a vision for 2050 [9]. The proposed strategy is addressed to a reduction of CO_2 emissions by at least 40 % by 2030, pursuing efforts towards 70 % by 2050, compared to 2008 level [10,11]. The transition towards the use of zero or low carbon fuels, as well as the introduction of innovative propulsion technologies are required actions to achieve these goals [12]. Hydrogen and hydrogen carriers-based technologies are seen as a promising solution for shipping decarbonization [13,14]. Fuel Cell systems as primary ship power sources are considered the most promising solutions for achieving carbon neutrality [15]. Renewable hydrogen usage in fuel cells-based powertrain systems may contribute to significant $CO_{2,eq}$ reductions compared to HFO and MDO, as well as a complete elimination of criteria air pollutants (CAP) emissions (i.e., NO_x, CO, SO_x,

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https://doi.org/10.1016/j.ecmx.2024.100539
Received 19 December 2023; Received in revised form 25 January 2024; Accepted 26 January 2024
Available online 28 January 2024

Nomenclature

BoP	Balance of Plant
CO_2	Carbon Dioxide
DWT	Dead Weight Tonnage
H_2	Hydrogen
LH_2	Liquid Hydrogen
LHV_{fuel}	Fuel Lower Heating Value
NH_3	Ammonia
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PSA	Pressure Swing Adsorption
RO-RO	Roll-on Roll-off
SOFC	Solid Oxide Fuel Cells
TEU	Twenty-Foot Equivalent Unit
TFC	Total Fuel Consumption
W_{Ship}	Propulsion System Nominal Power
nPGS	Power Generation System Efficiency
ndevice	Electrical Devices Efficiencies
xf-ME	Load Factor of Main Engine
xf-AUXs	Load Factor of Auxiliary Engines

PM) [16]. Despite this, the main drawback that hinders its diffusion in the shipping industry is related to its onboard storage and transportation challenges. Because of its low volumetric energy density, a larger storage space on board ships is usually required with respect to conventional marine fuels. For this reason, ammonia, biogas, Synthetic Natural Gas (SNG), and liquid organic hydrogen carriers (LOHCs, e.g., methanol) [17,18] are higher energy density potential alternatives to be employed as low/zero carbon fuels for ships [19,20]. Recently, there is a growing recognition that ammonia as a renewable and sustainable zero-carbon fuel has the potential to substitute conventional fossil fuels in modern combustion systems [21,22].

For example, ammonia is easier and less expensive to be transported than hydrogen, since it is stored in liquid form at ambient temperature, and 8 bar vapor pressure [23].

The use of renewable hydrogen carriers, to abate both CO_2 and CAP emissions inherently implies changing the propulsive set-up of current ships from thermal to electric [24]. This means replacing current main and auxiliaries ICEs with electric motors, powered by batteries and/or and fuel cell technologies [25]. The most mature and commercialized fuel cell type is the Proton Exchange Membrane Fuel Cell (PEMFC), which must be fed with high purity hydrogen. On the other hand, the deployment of high temperature fuel cell systems, i.e., Solid Oxide Fuel Cells (SOFCs), and Molten Carbonate Fuel Cells (MCFCs), is growing motivated by their capability to operate directly with fuels like ammonia, biofuels, and synthetic renewable carbonaceous fuels. In particular, ammonia can be directly used as fuel for SOFCs and MCFCs, since the high operating temperature (650–800 °C) allows achieving the ammonia cracking into nitrogen and hydrogen directly on the anodic electrode surface [26,27].

Literature review

The transition towards alternative fuels and energy systems onboard ships is deeply investigated in the scientific literature, with the aim of reducing CO2 emissions. Rivarolo et al. [28] compared, by evaluating different parameters (i.e. volume, weight, cost, emissions, etc) four different vessels and by comparing for each of them different powertrain solutions (i.e. PEMFC with liquid, compressed or MH stored hydrogen, SOFC with LNG, ICE fueled by MDO, MEOH, LNG, NH3). Results highlighted that the H2-based solutions represented the best solution in case of small ships (low power) and limited routes. Instead, for large ships and long routes, the traditional solutions were the optimal ones due to the strong constrains related to the required volume for the fuel storage.

Moreover, the interest towards the use of ammonia as hydrogen carrier for maritime transport decarbonization, is expanding rapidly. Seddiek et al. [29] investigated the usage of blue/green ammonia as a marine alternative fuel from environmental and economic perspectives. They compared three different propulsion systems to be installed on board a RO/RO vessel: a heavy fuel diesel engine, a blue/green ammonia diesel engine and a blue/green solid oxide fuel cell (SOFC). The results demonstrated the environmental effectiveness of the SOFC green ammonia-fueled ship, with a reduction of greenhouse gas (GHG) emissions of 93.4 % and 92 % compared with the traditional propulsion system. Wu et al. [30] analyzed an ammonia based SOFC powertrain system on board an ocean-going vessel from the economic and environmental perspective. They demonstrated that the proposed system was economically and environmentally viable for deep-sea shipping applications. Ye et al. [31] investigated electric propulsion systems for a water taxi and container ship powered by a hydrogen-based PEMFC in terms of system energy and exergy efficiency, fuel consumption, mass and volume, environmental impacts and cost. They studied onboard gaseous hydrogen storage or liquid ammonia storage coupled with onboard cracking. In absence of any carbon policy measures, the authors demonstrated an increase in costs compared to conventional powertrain systems of about 116 % and 105 %, respectively – despite showing a 91 % reduction of CO_2 emission. Percic et al. [32] analyzed the viability of different fuel cell types fed by hydrogen and ammonia, i.e., a low-temperature fuel cell (PEMFC) and a high-temperature fuel cell (SOFC), used as powertrain option of three Croatian Ro-Ro passenger ships. For the proposed systems, the authors carried out both a Life-Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA), and they compared the results with the existing diesel power systems. The results of the research indicated that fuel cell systems have a lower impact on the environment than a diesel-powered ship, with a reduction of up to 84 % in $CO_{2\text{-}eq}$ emissions when green ammonia is used. From the profitability perspective, they calculated that fuel cell systems fed with blue ammonia involve an increase in costs of 27 %–43 %, for PEMFC and SOFC systems respectively, with respect to the diesel-powered ship.

Contribution of the study and novelty

Despite the previous studies demonstrated the possibility of using ammonia-based technologies as powertrain systems for commercial ships, there is still a gap related to the evaluation of its applicability on board ships. As matter of fact, few studies in the technical literature described the viability of this solution from environmental and economic perspectives, and no study deals with the feasibility in installing these new powertrain systems considering the realistic ship's constraints.

In this context, the contribution of this study concerns a detailed feasibility analysis devoted to evaluate the energy performances (i.e fuel consumption) and the technical issues (i.e. the mass/volume of the components) related to the replacement of conventional engines with ammonia based-fuel cell systems for vessels propulsion.

The novelty consists of proposing a methodology for designing these new powertrain systems to be installed on board ships by applying a modelling approach based on the thermochemical and electrochemical analyses carried out in Aspen Plus environment.

In this study, it is highlighted that in order to support the implementation of ammonia fuel cells systems, in accordance with the IMO's ambitious plans for zero carbon emissions, it is necessary not only to evaluate the attended perùformances of these technologies, but also to investigate how their integration can affect the design of a new propulsion system on board a vessel.

Thus, this paper proposes the first study devoted to the feasible design of ammonia-based fuel cells by presenting preliminary configurations thought for a typical container ship.

The findings of this study will pave a support to the implementation of ammonia as an attractive hydrogen carrier, useful for replacing conventional powering solutions for naval propulsion with new cleaner technologies.

Materials and method

In this paper, ammonia-based power generation systems for the propulsion of zero-CO_2 vessels are analyzed through a design and modeling approach. Results, in terms of operating conditions and performances, have allowed to carry out a feasibility assessment related to the installation of the proposed powertrain systems on board vessel.

Powertrain system configurations

The first goal of this study concerns the design and the modeling of two power generation systems for supplying a ship propulsion system. Fig. 1 illustrates the proposed powertrain systems.

For both the systems, the propulsion system consists of an electric motor which, through a gearbox (mechanical efficiency, η=95 %), actuates the propeller shaft. The electric motor is supplied with electric power that comes from the PEMFC or SOFC, regulated with a AC/AC frequency converter (power electronics efficiency, η = 97 %) [8]. In each case, the electric power from the power generation systems can be used to supply the electric utilities available onboard a ship. A DC/DC converter (η = 97 %) and a DC/AC inverter (η = 97 %) are needed to regulate the power generation systems output voltage and to supply electricity in AC. Moreover, in order to distribute electricity to the different utilities, an AC switchboard and a transformer are needed.

Design and modeling approach

The design and modeling approach consists of two main steps (Fig. 2). In the first step, two NH_3-based power generation systems are defined and analyzed: i) a NH_3-based Proton exchange membrane Fuel Cell (PEMFC) system; and ii) the NH_3-based Solid Oxide Fuel Cell (SOFC) system. Each system and their Balance of Plant (BoP) is modelled in Aspen Plus™ environment. The second step consists in evaluating the feasibility of installing the proposed powertrain systems on board a ship, sizing the system according to the ship power requirements, calculating the fuel consumptions according to the ship typical load profile and defining the mass and the volume of the proposed power generation systems in comparison with a conventional diesel powertrain system. For this purpose, we use a container ship as a case-study.

Power generation system based on polymer electrolyte membrane fuel cell technology

The model flowsheet of the power generation system based on the PEMFC technology is depicted in Fig. 3. The system's BoP performs the NH_3 cracking, H_2 production and purification processes. The H_2 purification is carried out by means of a Pressure Swing Adsorption (PSA). The PEMFC system is modeled following a modular architecture in which each sub-model is conceived as a plant section that interacts with components by means of mass and energy fluxes. A brief description of the components employed in the Aspen model is reported in Table 1.

In order to define the PEMFC electrical performance, the available single cell polarization curve (the polarization curve is obtained by the manufacturer, and it is a confidential and non-disclosable data) is implemented in a block run calculator.

The NH_3, stored in liquid state al 20 °C and 8.8 bar, is separated in two fluxes. The first one (stream #1) is sent to the catalytic burner (C. BURNER) which, together with the purge gas (stream #12) from the PSA unit and pre-heated air (stream #19) at 190 °C, ensures the production of the required heat for the NH_3 cracking reaction. The second one (stream #2) is vaporized and superheated in the heat exchanger HE-1 (21 °C) and HE-2 (155 °C), respectively. After expanding down to the cracker unit (1.1 bar) by means of a throttling valve, it is sent to the cracking reactor where it is split into nitrogen and hydrogen at 550 °C. The syngas (stream #7) is cooled down to 102 °C in the heat exchanger HE-2 before entering the NH_3 adsorber, in which the residual ammonia (part per million) is removed. In order to reach the operating conditions (pressure and temperature) of the PSA that works with a Hydrogen Recovery Factor equal to 0.9, stream #9 is compressed by means of an

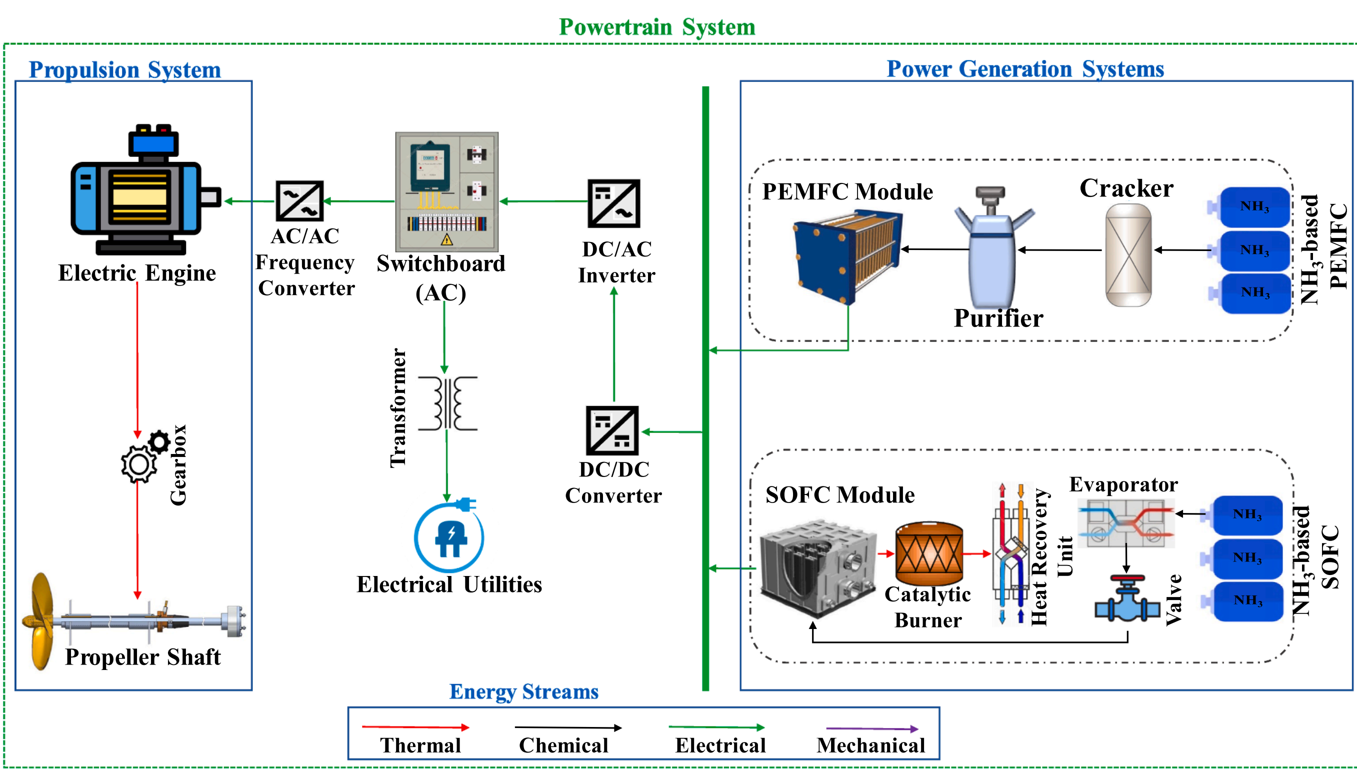

Fig. 1. Powertrain system schematic layout.

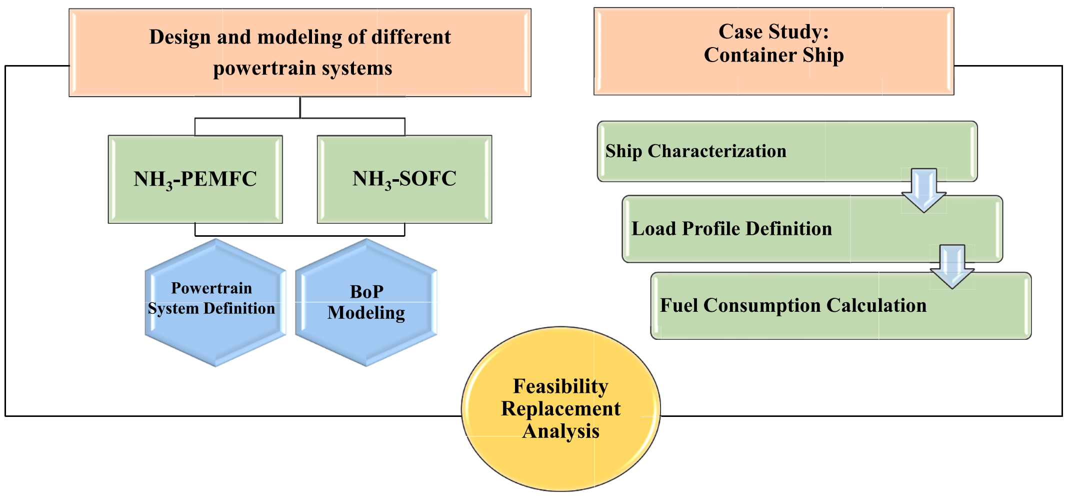

Fig. 2. Flowchart of the analysis method.

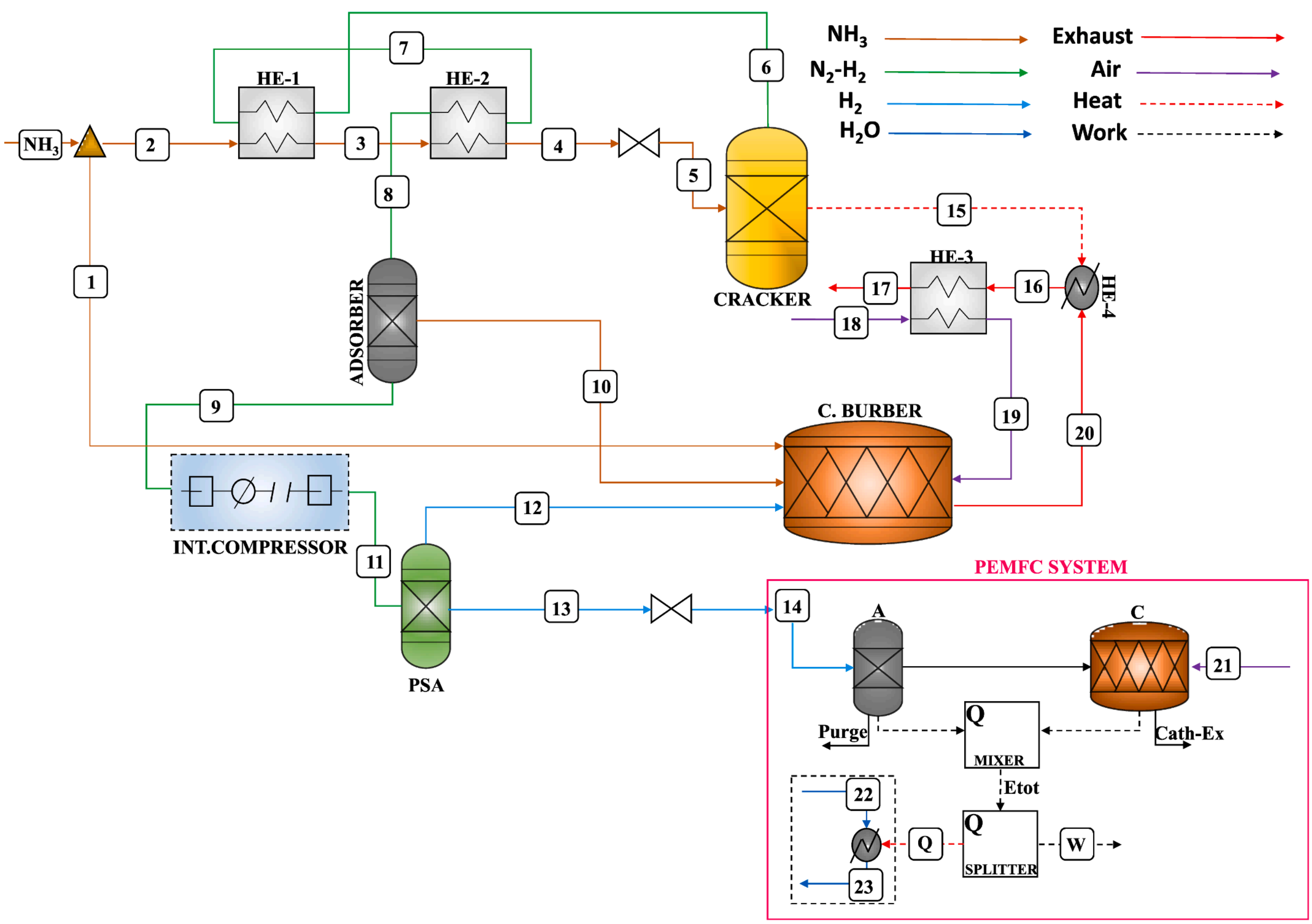

Fig. 3. Layout of NH3-based PEMFC power generation system.

intercooled compressor up to 9 bar (the membrane operating pressure in the feeding side), at 40 °C. The pure hydrogen (stream #13) heated up to 60 °C, expands down to the PEMFC operating pressure (8 bar) by means of a valve. The water-cooling process allows recovering low-temperature heat, which could be useful to supply a thermal load.

The PEMFC electrical performances (current, voltage and electric power) are estimated by using a Fortran block calculator in which the empirical equation, proposed by Kim et al. [34] is implemented. The empirical equation is:

$$V_{cell} = V_0 - b \bullet ln(J) - R \bullet J - m \bullet exp(-n \bullet J) \quad (1)$$

where V_0 (V) is the reversible cell potential, J is the current density (A cm^{-2}), b (V/dec) is the Tafel slope, R (Ω cm^2) is the ohmic resistance, m (V) and n (cm A^{-1}) are parameters that account for the mass transport

Table 1
Description of the components used in Aspen Plus for the NH3-based PEMFC flowsheet.

Block Name	Block Type	Description
CRACKER	RGIBBS	The cracker is modeled by using the *RGibbs* unit operator block where no reaction kinetics are applied. The *RGibbs* uses the Gibbs free energy minimization to calculate the equilibrium and does not require specified reaction stoichiometry. The cracking reaction is: $2NH_3 \leftrightarrow 3H_2 + N_2$ The Gibbs free energy of the reaction system (for k species) is: $G^t = \sum_{i=1}^{k} n_i \bullet \mu_i$ where n_i is the moles number of species i, and μ_i is its chemical potential. The conversion of the NH3 is equal to 99 % (by assuming Ni-based catalyst) at a fixed temperature equal to 550 °C. The specific energy for cracking reaction is 46 kJ/mol_{NH3}.
HE-n	HEATX	The heat exchangers are modeled by using the HeatX that can perform shortcut or detailed rating calculations for most types of four-stream heat exchangers. For a two-stream exchanger the set of equations is: $Q = \dot{m}_{cold} \bullet \Delta h_{cold}$ $Q = \dot{m}_{hot} \bullet \Delta h_{hot}$ $Q = U \bullet A \bullet LMTD$ where U (kW/m^2 K) is the heat transfer coefficient, A (m^2) is the heat exchange area and LMTD is the log-mean temperature difference.
PSA	SEP	The PSA is modeled by means of *Sep,* that is a separator which splits the entering fuel into two fluxes, according to an assigned split fraction, which corresponds to the selected purifier system efficiency, set equal to 90 % according to ref. [33].
INTERCOOLED COMPRESSOR	MCOMPR	The intercooled compressor is modelled by using the Mcompr block, which changes stream pressure and temperature by means of different stages compression. The polytropic efficiency of the compressor is assumed equal to 80 % and the cooling temperature is 40 °C. The compression ratio is 9.
CATALYTIC BURNER	RSTOIC	This component is modeled by means of *RStoic* that is a reactor in which the stoichiometry is known. The combustion reactions are: $H_2 + 0.5O_2 \rightarrow H_2O$ $4NH_3 + 3O_2 \rightarrow 6H_2O + 2N_2$
PEMFC UNIT	ANODE SIDE (SEPARATOR) CATHODE SIDE (RSTOIC) QMIXER/ QSPLITTER	The anode (A) is modeled as a separator unit in which purge hydrogen is separated from the reactant hydrogen (the H2 utilization factor is 97 %) of the outlet that is sent to the stoichiometric reactor that is used to model the cathode side (C) in which the oxygen reacts with hydrogen producing water. $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ The basic model assumptions are: (i) steady-state, (ii) isothermal conditions, (iii) ideal gas mixtures, (iv) negligible pressure drop. Two specific block calculators are used to solve the energy balance of the PEMFC system: the thermal Mixer block (QMIXER) and the thermal Splitter block (QFSPLIT). The thermal Mixer block is used to carry out the energy balance, considering the sensible enthalpy changes of the feeding streams at the anode and the cathode sides and the heat of electrochemical reactions. The thermal Splitter block (QFSPLIT), instead, is used to separate the output energy flux, in terms of work (W, the electrical power), and heat (Q, the thermal power). The operating temperature and pressure of the PEMFC unit are fixed equal to 60 °C and 8 bar, respectively.
Equation of State: Peng-Robinson		

overpotential. These coefficients are calculated by applying a regression technique on the polarization curve obtained by the manufacturer, which is a confidential and non-disclosable data.

By considering the cells number, the stacks number and the operating current, the electric power generated is calculated as:

$$W_{el,PU} = N_{stack} \bullet n_{cell} \bullet V_{cell} \bullet I \tag{2}$$

Power generation system based on solid oxide fuel cell technology

The second analyzed power generation system consists of a NH_3-based SOFC system. This fuel cell system does not require the fuel to be cleaned by energy-intensive external cracking and extensive purification since their high operating temperature provides the flexibility to crack the ammonia inside the anode electrode [29]. The model flowsheet of the power generation system based on the SOFC technology is depicted in Fig. 4 and refers to the plant BoP in which the NH_3 cracking process occurs on the anode side. Also in this case, the SOFC system is modeled by following a modular architecture in which each sub-model is conceived as a plant section that interacts with components by means of mass and energy fluxes. A brief description of the components employed in the Aspen model is reported in Table 2.

The NH_3, stored at 20 °C and 8.8 bar, is vaporized (HE-1) and preheated (HE-2) by using the exhaust gasses (stream #25) coming from the catalytic burner (C. BURNER). In the throttling valve the ammonia expands before entering the anode side of the fuel cell. The exhaust gases, before being vented to the atmosphere, are used both to preheat (HE-3) the cathodic air (AIR) and to generate (HE-4) steam for thermal loads onboard the vessel. In order to simulate the SOFC behavior from a thermodynamic point of view, the anode and the cathode have been modeled by using different components, as suggested in [35]. All the components employed in the model are widely described in Table 2.

The SOFC electrical performances (current, voltage and electric power) are estimated by using a Fortran block calculator in which the equation of the single cell polarization curve, obtained from experimental data, is implemented.

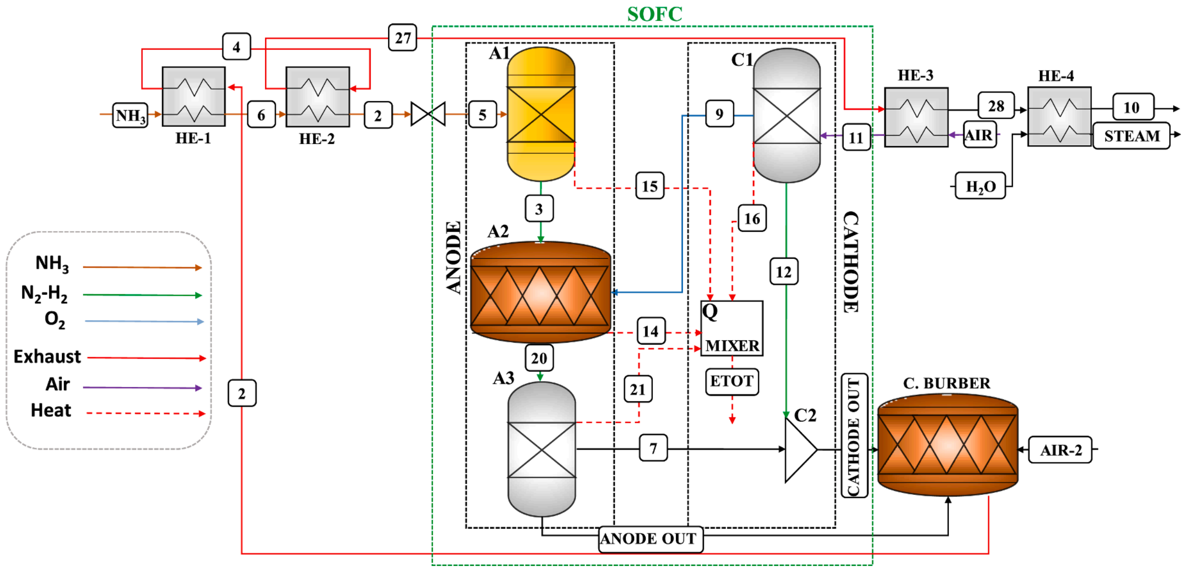

Fig. 4. Layout of NH3-based SOFC power generation system.

Modeling assumptions

The main modelling assumptions are:

- The nominal power capacity (size of the FC power unit) for each power generation system (PEMFC and SOFC units) are assigned equal to the nominal power of the reference main diesel engine
- For both fuel cell-based powertrain systems, the auxiliary engines have been eliminated. Thanks to the modular nature of fuel cells and their flexible performance at partial load, it is possible to envisage a control strategy in which only some fuel cell modules operate at full load, while others remain in hot stand-by. Alternatively, each fuel cell module could operate at partial load, to supply the power normally requested to the auxiliary ICE. The development of the control strategy to perform such operation is out of the scope of this work, but it would demonstrate a more flexible operation.
- The estimation of the fuel consumption has been carried out considering the ship mission profile and the efficiency curves of the selected power generation systems.

Case study

In order to verify the feasibility of installing the proposed powertrain systems on board a ship, the example of a container ship as case-study is considered. The vessel specification, the fuel cell modules characteristics, as well as the ammonia storage technologies are defined as follows.

Vessel

The layout of the container ship considered in this analysis is depicted in Fig. 5.

It shows a length overall (LOA) of 134.4 m, a breath extreme of 22.5 m, a draught of 8.7 m and shows a Dead Weight Tonnage (DWT) of about 11,271 tons. The reference ship is equipped with 8.4 MW main Diesel engine (ME) and uses 3.5 MW auxiliary engines (AEs), which characteristics in terms of mass and volume are reported in Table 3 [37].

Once selected the ship, the feasibility analysis is performed by sizing each powertrain system according to the ship power requirements, calculating the fuel consumptions according to the ship typical load profile and defining the mass and the volume of the proposed power generation systems.

The selected ship usually operates medium-distance voyages; in particular, for this study we consider a typical voyage, characterized by a cruise duration of 172 h, and an average speed of 18.5 knots. Fig. 6 illustrates the typical container ship mission profile considering the load factors (the ratio between the operating power and the installed power) of the main engine ($x_{f\text{-}ME}$) as well as the load factors of the auxiliary engines ($x_{f\text{-}AUXs}$).

It is important to underline that, for safety reasons, the size of the main marine diesel ICE installed on board (8.4 MW) is bigger with respect to the maximum power demand (mission profile) required during the navigation (the peak required power is 5.46 MW). This choice allows to meet every load variation according to every probable weather condition.

Taking into account the ship mission profile and considering the specifics of each analyzed power generation system, the total fuel consumption (TFC) in each load condition (*i*) to comply the ship voyage has been calculated according to ref [40] as:

$$TFC = tf \int 0 \frac{(x_{f-ME}(t)W_{ME} + x_{f-AUXs}(t)W_{AUXs})}{LHV_{FuelPGS}(i)_{devices}(i)} dt \quad (3)$$

where, W_{ME} is the installed power of the main engine devoted to the propulsion and W_{AUXs} is the total installed power of the aux. engines, LHV_{Fuel} represents the fuel lower heating value and (17.7 and 120.0 MJ/kg for ammonia and hydrogen, respectively),nPGS is the power generation system efficiency, and nDevicesre fers to the electrical devices efficiencies. The term t_f represents the cruise time-end (172 h).

Knowing the amount of fuel needed to satisfy the vessel's power load profile, the systems' net efficiencies are calculated according to the following equations:

$$_{e,net} = \frac{\sum_{t=0}^{tf}(X_{f-ME}(t)W_{ME} + X_{f-AUXs}(t)W_{AUXs} + W_{Compressor})}{TFC} \quad (4)$$

Fuel cell modules

The NH$_3$-based PEMFC power generation system is characterized by a 100 kW PEMFC system [41]. Each FC module is fed with pure hydrogen at 8 bar and its operating temperature is 60 °C. The system shows a power density (@ 280 V and 360 A) and volumetric power density of 256 kW/ton and 99 kW/m^3, respectively.

For the NH3-based SOFC power generation system, the technical specifications of the commercial system developed by Bloom Energy are considered [42]. Each FC module shows an operating temperature of 750 °C and a cumulative electrical efficiency (LHV net AC) ranging between 65 and 53 %. The system shows a power density and volumetric power density of 18.4 kW/ton and 10.1 kW/m^3, respectively. Table 4

Table 2
Description of the components used in Aspen Plus for the NH3-based SOFC model.

Block Name	Block Type	Description
HE-n	HEATX	The heat exchangers are modeled by using the HeatX that can perform shortcut or detailed rating calculations for most types of four-stream heat exchangers.
C.BURNER	RSTOIC	This component is modeled by means of *RStoic* that is a reactor in which the stoichiometry is known. The combustion reaction is: $H_2 + 0.5O_2 \rightarrow H_2O$
SOFC UNIT	ANODE SIDE (GIBBS REACTOR, STOICHIOMETRIC REACTOR, SEPARATOR)	Gibbs reactor (A1): in this reactor the ammonia cracking (46 kJ/mol NH3) occurs: $2NH_3 \rightarrow 3H_2 + N_2$It is assumed that NH3 is totally converted into H2 and N2 (by considering the high
	CATHODE SIDE (SEPARATOR, MIXER)	SOFC operating temperature and the Ni-catalyst used in the anode side). Stoichiometric reactor (A2): in this
	Q MIXER	reactor the hydrogen oxidation is carried out: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$Separator (A3): the unreacted oxygen is separated to be again mixed to nitrogen. Separator (C1): the oxygen is separated by nitrogen and sent to the anode side for reacting with hydrogen Mixer (C2): the unreacted oxygen is mixed with the nitrogen to get the right cathode off-gas composition. The thermal mixer block is used to solve the energy balance of the SOFC taking into account the sensible enthalpy changes of the feeding streams at the anode and the cathode sides and the heat of electrochemical reactions [36]. The operating temperature and pressure are 750 °C and 1.1 bar, respectively. The H2 utilization factor is set equal to 0.8 (according to experimental data [35]).
Equation of State: Peng-Robinson		

Fig. 5. Typical layout of the container ship.

summarizes the technical data for the considered PEMFC and SOFC modules. The reader should consider that the commercial SOFC system is not designed for maritime applications, but rather for stationary high efficiency power generation applications. Consequently, the BoP is not optimized to minimize weight or footprint; hence the gravimetric and volumetric energy density values should not be interpreted as a standard for the shipping sector. Our choice of reference system is simply a reflection of the availability of complete information for a commercial unit.

Table 3
Main and Auxiliary engines technical characteristics.

Equipment	Volume (m^3)	Weight (tons)
Main Diesel Engine [38]	137.3	126.0
Auxiliary Diesel Engines [39]	116.0	83.0
Total	253.3	209.0

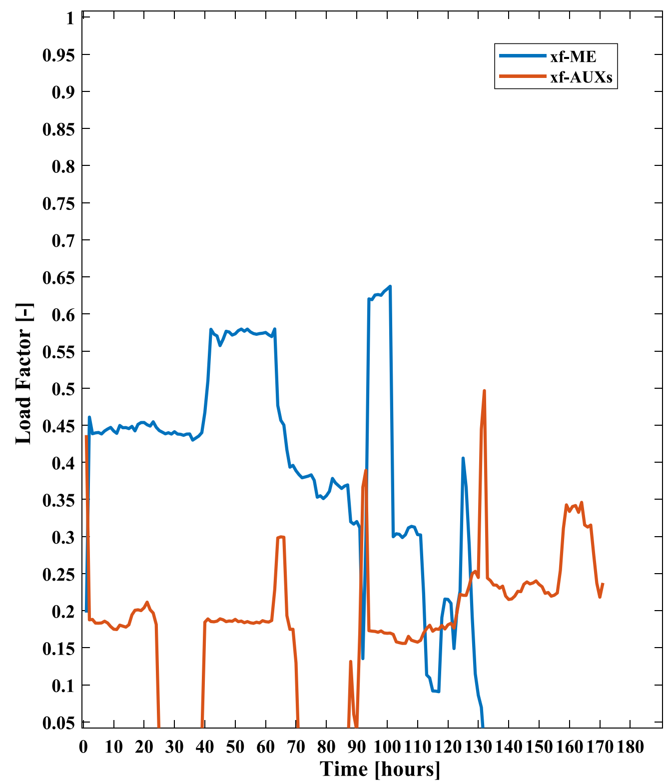

Fig. 6. Container ship mission profile.

Table 4
PEMFC and SOFC technical data.

Equipment	PEMFC	SOFC
Voltage and Current (V/A)	280/360	480
Efficiency (%)	37–56	54.0
Power Density (kW/ton)	256	18.4
Volumetric Power Density (m^3/ton)	99	10.1

Ammonia storage system

The ammonia is stored onboard at 8.8 bar and ambient pressure, hence in liquid form [43]. Table 5 summarizes the ammonia storage

Table 5
Storage technologies main characteristics.

	Liquid NH_3
Ref.	[43]
External Diameter (m)	2.5
Length (m)	4.5
Empty Mass (ton)	11.5
Internal Volume (m^3)	22.0

tanks characteristics.

Results

This section illustrates the technical results of the proposed powertrain systems in terms of: i) thermodynamic performances, ii) feasibility assessment and iii) economic issues.

Powertrain system based on proton exchange membrane fuel cells

The needed H_2 amount for feeding the PEMFC is calculated considering the PEMFC average efficiency and the trend variation of the load profile factors and the PEMFC operating condition under these load variations (depicted in Fig. 7). The H_2 consumption is calculated by taking into account eq. (1) and by matching the trend variation of the load profile with the system's power output, as reported in the Appendix. The PEMFC model is validated as reported in Ref. [44].

The overall H_2 consumption for the selected cruise is 32 tons, including the hydrogen needed to generate the electric power that the PEMFC must provide to operate the intercooled compressor.

The overall NH_3 consumption is then calculated to completely satisfy the H_2 required by the PEMFC. Considering that 8.24 kg of NH_3 are needed to produce 1 kg of H_2, the total NH_3 consumption is equal to 310 tons. Assuming a safety fuel margin of 10 %, the NH_3 amount that must be stored on board is 340 tons.

Table 6 lists the thermochemical properties of each stream in the NH_3-based 8.4 MW PEMFC power generation system, and Table 7 summarizes its thermodynamic performance results.

Table 6
Thermochemical properties of each stream in the NH_3-based 8.4 MW PEMFC system.

Flows	Mass flow rate (ton/h)	T (°C)	P (bar)	Composition
NH_3	4.57	20	8.8	100 %–NH3
1	0.97	20	8.8	100 %–NH3
2	4.21	20	8.8	100 %–NH3
3	4.21	40	1.1	100 %–NH3
4	4.21	155	1.1	100 %–NH3
5	4.21	155	1.1	100 %–NH3
6	4.21	550	1.1	74.8 %–H2, 24.9 %–N2, 0.3 %–NH3
7	4.21	177.2	1.1	74.8 %–H2, 24.9 %–N2, 0.3 %–NH3
8	4.21	102.3	1.1	74.8 %–H2, 24.9 %–N2, 0.3 %–NH3
9	4.18	102.3	1.1	75 %–H2, 25 %–N2
10	0.02	102.3	1.1	100 %–NH3
11	4.18	40	9	75 %–H2, 25 %–N2
12	3.54	40	9	23 %–H2, 77 %–N2
13	0.78	60	9	100 %–H2
14	0.78	60	8	100 %–H2
16	27.82	211	1.1	78.7 %–N2, 15.2 %–O2, 6.1 % H2O
17	27.82	74.9	1.1	78.7 %–N2, 15.2 %–O2, 6.1 % H2O
18	23.70	20	1.1	75 %–N2, 25 %–O2
19	23.70	190	1.1	75 %–N2, 25 %–O2
20	27.82	761.6	1.1	78.7 %–N2, 15.2 %–O2, 6.1 % H2O
21	839.50	20	1.1	75 %–N2, 25 %–O2
22	841.85	70	1	100 %–H2O
23	841.85	58	1	100 %–H2O

Powertrain system based on solid oxide fuel cells

The NH_3 consumption is calculated starting from the SOFC average efficiency, considering the trend variation of the load profile factors and the SOFC operating condition, as depicted in Fig. 8.

For the selected cruise, the overall ammonia consumption is 196.7 tons. Assuming a safety fuel margin of 10 %, the ammonia amount that must be stored on board is 216.5 tons. The thermochemical properties of each stream in the 8.4 MW NH_3-SOFC system process flow diagram are summarized in Table 8, and Table 9 shows the thermodynamic performance results. The SOFC model has been validated as reported in

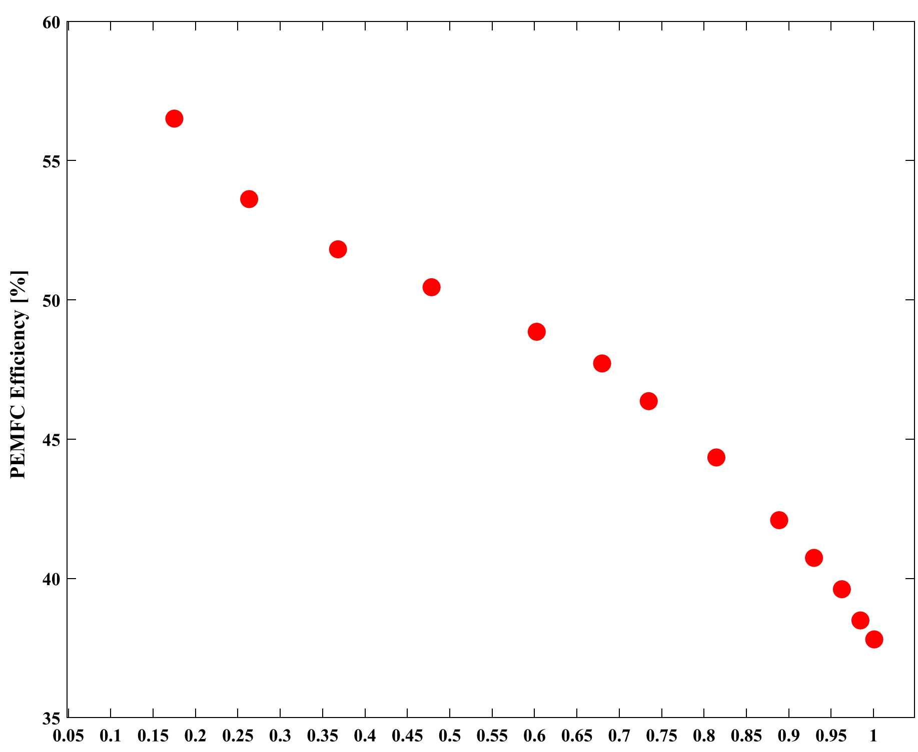

Fig. 7. PEMFC efficiency curve.

Table 7
Simulation results.

Components Technical Data	
Cracker	
Temperature (°C)	550
Heat Duty (MW)	5.7
Int.Compressor	
Size (MW)	1.5
Heat Exchanger HE-2	
Heat Duty (kW)	349.4
Min Temperature Approach (°C)	22
Effectiveness, ε (%)	83.8
C. Burner	
Outlet temperature (°C)	613.6
Heat Exchanger HE-3	
Heat Duty (MW)	1.9
Min Temperature Approach (°C)	15.4
Effectiveness, ε (%)	91.5
PSA	
Heat Duty (kW)	123.5
PEMFC system	
Size (MW)	8.4
Performance	
TFC (tons)	310.0
Average net efficiencynenet (%)	43

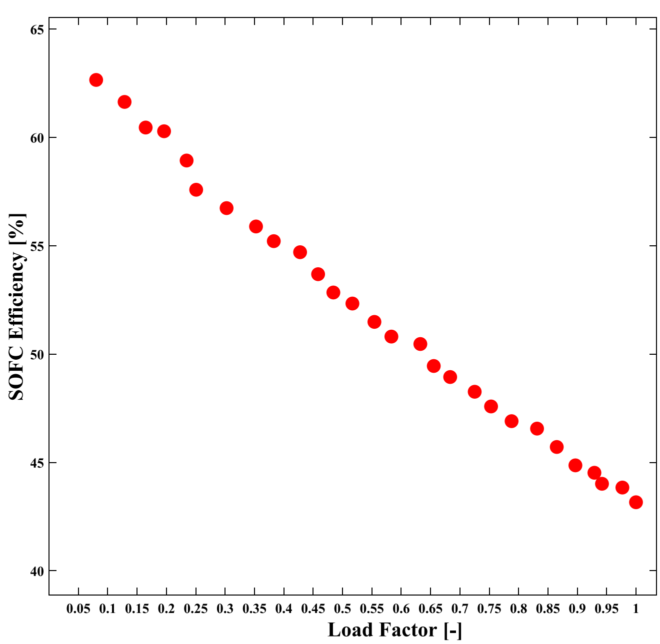

Fig. 8. SOFC efficiency curve vs the operating power.

Ref. [35].

It can be noticed that the available heat from the catalytic burner allows having ammonia vaporizations and pre-heating, assuming a good heat exchange effectiveness (73.5 %). Moreover, the high temperature of ammonia exiting the HE-2, allows pre-heat air in entrance the cathode, assuming a high heat exchange effectiveness (83.4 %).

Table 8
Energy and mass balances of 8.4 MW NH_3-based SOFC system.

Flows	Mass flow rate (ton/h)	T (°C)	P (bar)	Composition
NH_3	3.19	20	8.8	NH_3-100 %
2	3.19	600	8.8	NH_3-100 %
3	3.19	750	1.1	H_2-75 %, N_2-25 %
4	115.67	807	1.1	N_2-76.9 %, O_2-16.5 %, H_2O-6.6 %
5	3.19	600	1.1	NH_3-100 %
6	3.19	21	8.8	NH_3-100 %
7	22.01	750	1	O_2-100 %
9	25.70	750	1.1	O_2-100 %
10	115.67	152	1.1	N_2-76.9 %, O_2-16.5 %, H_2O-6.6 %
11	110.12	650	1.1	N_2-79 %, O_2-21 %
12	84.42	750	1.1	N_2-100 %
20	28.90	750	1.1	O_2-65.5 %, H_2O-20.7 %, N_2-8.6 %, H_2-5.2 %
25	115.67	833.6	1.1	N_2-76.9 %, O_2-16.5 %, H_2O-6.6 %
27	115.67	773.7	1.1	N_2-76.9 %, O_2-16.5 %, H_2O-6.6 %
28	115.67	215.7	1.1	N_2-76.9 %, O_2-16.5 %, H_2O-6.6 %
AIR	110.12	20	1.1	N_2-79 %, O_2-21 %
AIR-2	2.27	20	1.1	N_2-79 %, O_2-21 %
ANODE OUT	6.47	750	1.1	N_2-25 %, H_2-15 %, H_2O-60 %
CATHODE OUT	106.51	750	1.1	N_2-81.3 %, O_2-18.7 %
H_2O	2.77	20	1.1	H_2O-100 %
STEAM	2.77	120	1.1	H_2O-100 %

Table 9
Simulation results.

	NH_3-based SOFC system
Components Technical Data	
Heat Exchanger HE-2	
Heat Duty (MW)	1.3
Min Temperature Approach (°C)	209.9
Effectiveness, ε (%)	73.5
Heat Exchanger HE-3	
Heat Duty (MW)	20.2
Min Temperature Approach (°C)	125.3
Effectiveness, ε (%)	83.4
C. Burner	
Temperature (°C)	837.0
SOFC system	
Size (MW)	8.4
Performances	
TFC (tons)	196.7
Average Net efficiencynenet (%)	57.0

Powertrain system feasibility assessment

The feasibility assessment is performed by comparatively accounting masses and volumes for the two fuel cell-based powertrains and the reference diesel ICE scenario. As far as the NH_3-based PEMFC system is concerned, the mass and volume of the PEMFC power generation system are calculated by taking into account the PEMFC technical data (Table 4). The total volume and mass of the stored NH_3 is calculated taking into account the storage technologies characteristics. Table 10 lists the mass and volume of each component of the plant in the engine room and the total mass and volume of the stored NH_3 in the fuel room.

Table 10
Volume and Mass for the NH3-based PEMFC Configuration [33,41].

	Volume (m^3)	Mass (ton)
Engine Room		
PEMFC	84.7	32.8
Purifier	27.3	11.2
Cracker	8.7	4
Converter	2.7	1
Inverter	4	3
Propulsion Motor	30	20
Heat Exchangers	3.8	6.4
Installation, instrum., control etc.	1.8	0.8
Total	163.0	78.2
Fuel Room		
Stored NH_3	681.4	696.8

Comparing the total volume and mass of the proposed power generation system in the engine room with the reference diesel configuration (with a total mass and volume of 209 tons and 253 m^3, respectively), the new power unit occupies 35.5 % less space and 62.5 % less mass, creating additional space in the engine room to store fuel.

On the other hand, in the fuel room, considering that for the same cruise the diesel fuel amount equals 99 tons (i.e., 118.8 m^3), the stored NH_3 exceeds the diesel reference case both in terms of volume and mass.

As far as the NH_3-based SOFC power generation system is concerned, the feasibility assessment is performed considering the SOFC technical data reported in Table 4. The total volume and mass of the stored NH_3 is calculated considering the storage technologies characteristics. Table 11 lists the mass and volume of each component of the plant in the engine room and the total mass and volume of the stored NH_3 in the fuel room.

The results show that the required volumes and masses needed to install the proposed powertrain system exceed the ones of the diesel system (243 m^3 in volume and 209 tons in weight) both in the engine room and in the fuel room.

Discussion

From the analysis of the results of each power generation system, it is highlighted that the SOFC-based propulsion system reaches the highest efficiency (57 %) with respect to the PEMFC one (43 %) as well as with respect to the reference case (50 %). Moreover, both the proposed configurations require higher volume and mass for their installation on board.

Comparison with the state of art

The possibility of using fuel cells on board ships has been analyzed in ref. [45], in which some research and demonstration projects, based on the development of fuel cells systems for maritime applications, are presented. In [45] it was highlighted that the most common type for installation in maritime applications is the PEMFC system fueled by hydrogen for small-medium size applications (i.e tourist boats, canal boats, and passenger/car ferries). The SOFC technology is mainly proposed for bigger vessels (i.e. cruise ships and cargo ships). Table 12 illustrates the available information on research projects related to PEMFC and SOFC fed by different fuels and used as propulsion systems.

This table gives a clear idea that the number of projects on the ammonia usage is very limited and details on performances are not already available (or not disclosed).

As matter of fact, the EU-funded ShipFC project [57], is the first NH_3–powered fuel cell on a vessel. This project is devoted to the installation of an offshore vessel retrofitted with a 2 MW NH_3 SOFC, allowing to sail with a cleaner fuel for up to 3000 h annually.

Moreover, in the technical literature few studies on the NH3 usage in fuel cell power systems for vessel propulsion, are available for energy and a size-based benchmark. Table 13 illustrates and compares the results of the proposed study with some data related to the available research papers.

It is worth noticing that the estimated efficiencies for the proposed PEMFC and SOFC based systems are in accordance with results obtained in other studies.

Preliminary economic evaluation

By considering the results of each power generation system, it is highlighted that higher volume and mass are required in comparison with the diesel engine system. It means that installing the proposed systems involves having a vessel's mass carrying capacity reduction. Since the carrying capacity of a commercial ship such as a container ship is accountable in terms of transportable TEU (twenty-foot equivalent unit) [61]. Fig. 9 shows the calculated carrying capacity reduction expressed in TEU.

The best solution is represented by the NH_3-based PEMFC powertrain system, for which the vessel carrying capacity in terms of transported TEU is reduced by about 3.3 %. The worst solution, instead, is represented by the NH_3-based SOFC powertrain system, for which the vessel carrying capacity reduction increase to 4.8 %. The difference is mainly due to the higher volume and mass required in the engine room for installing the SOFC powertrain system, which is characterized by a much lower volumetric and gravitational power density compared to the PEMFC system. This entails the need of bulkier components, including heat exchangers, which become the second largest contribution to the increased volume and mass requirements for the SOFC-based scenario. This underlines the importance of increasing the power density of SOFC stacks and systems for heavy-duty transportation applications, lest eliminating the advantages associated with the higher energy conversion efficiency and fuel flexibility.

It is important to underline that, the reduction in vessel cargo capacity can represent a critical issue since it translates in an economic loss for the ship owners. As matter of fact, assuming a specific TEU cost of $1000/TEU [62], the economic loss associate with the respective cargo reduction for each powertrain system is readily found, as reported in Table 12.

€However, each fuel cell-based system is characterized by zero CO_2 direct emission. As matter of fact, the proposed systems allow avoiding 258.5 ton/CO_2 per each cruise (considering that 1 L of diesel produces 2.61 kg of CO_2 [63]). Considering that the EU Emission Trading System has been recently extended to the maritime sector the carbon tax (129 €/ton_{CO2eq}), an avoided cost for the emitted CO_2 equal to €33,332.0 must be considered. This means that, both the proposed solutions represent a valid option form an economic perspective.

Conclusion

This study concerns the design, modeling, and assessment of feasibility installation for two ammonia-based power generation systems for the decarbonization of the shipping industry: i) a NH_3-based PEMFC

Table 11
Volume and Mass for the NH3-based SOFC system [33,42,45].

	Volume (m^3)	Weight (tons)
Engine Room		
SOFC	821.8	451.1
Propulsion Motor	30	20
Converter	2.7	1
Inverter	4	2
Heat Exchangers	27.1	19.2
Inst., instrum., control	8.9	4.9
Total	894.5	498.2
Fuel Room		
Stored NH_3	355.4	402.2

Table 12
Overview of international research project on FC technologies for shipping.

Projects	Time Period	Country	Vessel	FC Type	FC Power	Fuel type	Fuel Storage
TecBIA [46,47]	2018–2022	Italy	Research vessel (ZEUS)	PEMFC	140 kW	H2	48 kg MH
HI-SEA[48]	2017–2022	Italy	Experimental plant	PEMFC	250 kW	H2	NA
Nemo H_2 [49]	2008-present	Netherlands	Passenger boat (Nemo H2)	PEMFC	65 kW	H2	24 kg CH2@350 bar
HYSEAS III [50,51]	2018–2022	Scotland	RoPax ferry	PEMFC	600 kW	H2	600 kg CH2@350 bar
FlegShip [45]	2019–2023	Netherlands/ France/ Norway	Self-propelledBarge (ZULU)	PEMFC	400 kW	H2	350 kg CH2@350 bar
Maranda[52]	2017–2022	European Union	Arctic research ship Aranda	PEMFC	165 kW	H2	CH2@300 bar
PaXell 2[53]	2019–2022	Germany	Cruise ship (AIDAnova)	PEMFC	60 kW	MeOH	NA
RiverCell[54]	2015–2022	Germany	Inland passenger ship	PEMFC	250 kW	MeOH	NA
					192 kW	H2	750 kg CH2@500 bar
ZEMSHIP[55]	2007–2014	Germany	Passenger ship FCS Alsterwesser	PEMFC	96 kW	H2	50 kg CH2@350 bar
METHAPU [45]	2006–2010			SOFC	120 kW	H2	1200 kg LH2
Nautilus -[56]	2020–2024	European Union	Cruise ship	SOFC	60 kW	LNG	
ShipFC [57]	2020–2024	Norway	Offshore vessel (Viking Energy)	SOFC	2 MW	NH3	NA
SchIBZ MS[58]	2009–2018	Germany	General cargo ship, yachts Forester	SOFC	100 kW	Diesel	NA

(NA: not assigned, CH2: compressed hydrogen, LH2: liquid hydrogen, MH: Metal Hydride, LNG: Liquid Natural Gas).

Table 13
Comparison among NH3 based FC technologies for shipping in the technical literature.

Research papers	Year	Vessel	FC type	FC power	Fuel system	System efficiency
Ye et al [31]	2022	Passenger water taxi	PEMFC	31 kW	NH3 cracking	36 %-43 % (in the operating range)
This study	2023	Container ships	PEMFC	8.4 MW	NH3 cracking	43 %
Wu et al. [30]	2022	Ocean-going vessel	SOFC	56.4 MW	NH3 cracking	60 %
Louvros [59]	2023	Container ship	SOFC	1.5 MW	NH3	60 %
Duong [60]	2023	General cargo	Hybrid power system (SOFC + PEMFC + other power subsystems)	5.4 MW	NH3 direct FC feeding	60.7 % (SOFC produces the 69.9 % of the total power)
This study	2023	Container ships	SOFC	8.4 MW	NH3 direct FC feeding	57 %

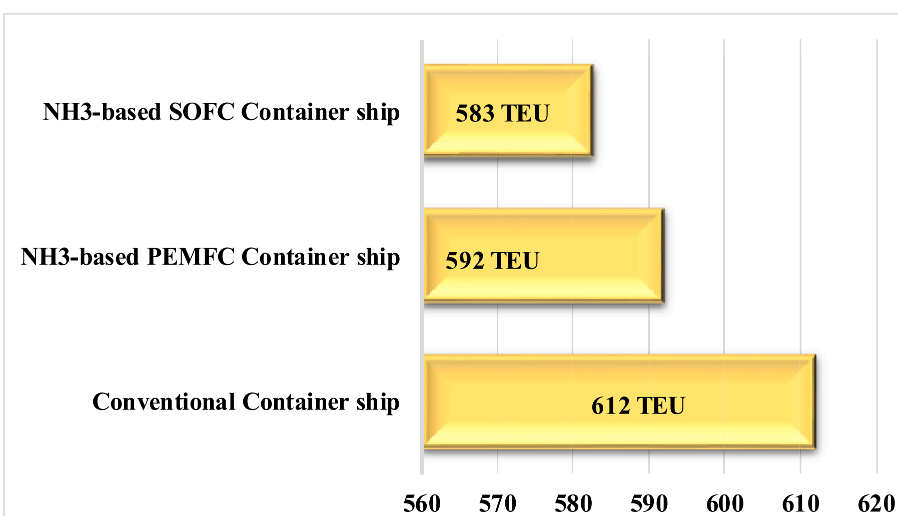

Fig. 9. Container ship TEU reduction for the considered powertrain systems.

system and ii) a NH_3-based SOFC system. From the design perspective, the power generation systems are conceived considering the integration of several commercial components, by defining the sizes, the masses, and the volumes. From a thermodynamic perspective, both systems are modeled in Aspen Plus™ environment following a modular architecture in which each sub-model is conceived as a plant section that interacts with components by means of mass and energy fluxes.

In order to assess the installation of the proposed powertrain systems on board vessels, a specific container ship, as case-study, is considered and the sizing of the systems according to the ship power requirements, the fuel consumptions according to the ship typical load profile, and the masses and the volumes of the proposed power generation systems in comparison with a conventional diesel powertrain system are evaluated. Results highlight that a lower NH_3 consumption (196.7 tons vs 310 tons) and a higher average net electric efficiency (57 % vs 43 %) are achieved for the SOFC-based propulsion system with respect to the PEMFC based one.

Form a feasibility perspective, the results demonstrate that for both the power generation systems higher volumes and masses are required in comparison with the reference diesel engine system. This means that the installation of the proposed systems involves having a vessel's mass carrying capacity reduction, expressed in terms of TEU.

The NH3-based PEMFC represents the best solution in terms of lower percentage of cargo reduction, equal to 3.3 %; the NH3-based SOFC, instead, requires a cargo reduction of 4.8 %.

Therefore, by comparing the proposed systems it is possible to notice that, the SOFC technology allows achieving better performance from the technical perspective, with lower fuel consumption and higher net electric efficiency with respect to the PEMFC one; however, this result is not confirmed from the feasibility perspective, since its higher volume and weight involves having a higher cargo reduction in comparison with the PEMFC system.

The reduction in vessel cargo capacity represents a critical issue for the implementation of low-carbon powertrains onboard ships since it directly translates in an economic loss for the ship owners. It is estimated that the cargo reduction for the NH3-based PEMFC and the NH3-based SOFC powertrain systems corresponds to an economic loss of 20,000 € and 30,000 €, per cruise, respectively. Finally, considering that each fuel cell-based system allows curbing direct CO_2 emissions to zero, and considering the current cost of carbon in the European Trading Scheme (129 €/ton_{CO2eq}), an avoided cost for the emitted CO_2 (€33,332.0) must be considered. This means that the avoided cost for the emitted $CO_{2,eq}$ may compensate the economic loss for the cargo reduction for both the proposed solutions. Next research activities will be focused on the economic assessment of the proposed systems, by evaluating investment costs, operating costs, maintenance costs and all the incentive strategies for assuring the economic competitiveness of these systems with respect to the traditional one.

CRediT authorship contribution statement

S. Di Micco: Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **V. Cigolotti:** Writing – review & editing. **L. Mastropasqua:** Writing – review & editing. **J. Brouwer:** Writing – review & editing, Conceptualization. **M. Minutillo:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This research was funded by the European Union – NextGeneration EU from the Italian Ministry of Environment and Energy Security POR H2 AdP MMES/ENEA with involvement of CNR and RSE, PNRR - Mission 2, Component 2, Investment 3.5 "Ricerca e sviluppo sull'idrogeno", CUP: I83C22001170006.

Appendix

A script in MATLAB environment has been implemented to calculate the fuel consumptions during the cruise for each configuration. It matches the trend variation of the load profile factors and the systems' operating condition under these load changes. The time step of the integration is 300 s, since the time interval of the chemical tanker load profile is 5 min. The interpolation between the power generation systems efficiencies and the load profile points has been realized using the spline function in MATLAB.

```
close all
x = Load_Power_Generation_System;
y = eta1*100;
x1 = 10:10:100;
XX = x1;
YY = spline(x.y.XX);
figure %%Efficiency curve with load profile
plot(x.y.'o');
hold on
plot(XX.YY);
% Fuel Consumption Calculation
for i = 1:length(powernormalized)
if powernormalized(i)==0 && powernormalized(i) < 0.09
eta(i) = 0;
C(i) = 0;
elseif powernormalized(i) > 0.09 && powernormalized(i)<=0.1
eta(i) = eta_nominal;
C(i) = powernormalized(i)/eta(i);
else
eta(i) = spline(x.y.powernormalized(i))/100;
C(i) = powernormalized(i)/eta(i);
end
Cf(i) = C(i)*8400;
end
```

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(*continued*)

close all

time = 0:300:(172*3600–300);
Fuel_Consumption_kW = cumtrapz(time.Cf);
Fuel_Consumption_ton = Fuel_Consumption_kW(end)/LHV_fuel
figure
plot(time/3600.Fuel_Consumption_kW)
%%CONSUMPTION OF AUXILIARY ENGINES
for i = 1:length(aux_normalized)
eta2(i) = 0 eta_nominal;
P_aux(i) = aux_normalized(i)/eta2(i)*3524;
end
time = 0:300:(172*3600–300);
AUX_Fuel_consumption_kW = cumtrapz(time.P_aux);
AUX_Fuel_consumption_ton = AUX_Fuel_consumption_kW(end)/LHV_fuel
%%CONSUMPTION OF COMPRESSOR
for i = 1:length(powernormalized)
if eta(i)==0;
P_compressor(i) = 0;
else %altrimenti
eta(i) > 0;
P_compressor(i)=(1.5*(H2consumption_kW(i)/120000000))/(0.08333*eta(i));
end
time = 0:300:(172*3600–300);
H2consumption_kW_compr = cumtrapz(time,P_compressor);
H2consumption_ton_compr = H2consumption_kW_compr(end)/120000000

References

[1] Ling-Chin J, Roskilly AP. Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study. Appl Energy 2016;181:416–34. https://doi.org/10.1016/j.apenergy.2016.08.065.

[2] Walker TR, Adebambo O, Del Aguila Feijoo MC, Elhaimer E, Hossain T, Edwards SJ, et al. Chapter 27 - Environmental Effects of Marine Transportation. In: Sheppard CBT-WSAEE (Second E, editor., Academic Press; 2019, p. 505–30. 10.1016/B978-0-12-805052-1.00030-9.

[3] Ampah JD, Yusuf AA, Afrane S, Jin C, Liu H. Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. J Clean Prod 2021;320:128871. https://doi.org/10.1016/j.jclepro.2021.128871.

[4] Zhao F, Yang W, Tan WW, Yu W, Yang J, Chou SK. Power management of vessel propulsion system for thrust efficiency and emissions mitigation. Appl Energy 2016;161:124–32. https://doi.org/10.1016/j.apenergy.2015.10.022.

[5] Gray N, McDonagh S, O'Shea R, Smyth B, Murphy JD. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv Appl Energy 2021;1:100008. https://doi.org/10.1016/j.adapen.2021.100008.

[6] Al Baroudi H, Awoyomi A, Patchigolla K, Jonnalagadda K, Anthony EJ. A review of large-scale CO_2 shipping and marine emissions management for carbon capture, utilisation and storage. Appl Energy 2021;287:116510. https://doi.org/10.1016/j.apenergy.2021.116510.

[7] de Fournas N, Wei M. Techno-economic assessment of renewable methanol from biomass gasification and PEM electrolysis for decarbonization of the maritime sector in California. Energy Convers Manag 2022;257:115440. https://doi.org/10.1016/j.enconman.2022.115440.

[8] Di Micco S, Minutillo M, Forcina A. Feasibility analysis of an innovative naval on-board power-train system with hydrogen- based PEMFC technology. E3S Web Conf 2021;312. https://doi.org/10.1051/e3sconf/202131207009.

[9] Godet A, Nurup JN, Saber JT, Panagakos G, Barfod MB. Operational cycles for maritime transportation: A benchmarking tool for ship energy efficiency. Transp Res Part D Transp Environ 2023;121:103840. https://doi.org/10.1016/j.trd.2023.103840.

[10] Prussi M, Scarlat N, Acciaro M, Kosmas V. Potential and limiting factors in the use of alternative fuels in the European maritime sector. J Clean Prod 2021;291:125849. https://doi.org/10.1016/j.jclepro.2021.125849.

[11] Initial IMO Strategy on reduction of GHG emissions from ships: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx, accessed 21/04/2022 n.d.

[12] Watanabe MDB, Hu X, Ballal V, Cavalett O, Cherubini F. Climate change mitigation potentials of on grid-connected Power-to-X fuels and advanced biofuels for the European maritime transport. Energy Convers Manag X 2023;20. https://doi.org/10.1016/j.ecmx.2023.100418.

[13] Korberg AD, Brynolf S, Grahn M, Skov IR. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renew Sustain Energy Rev 2021;142. https://doi.org/10.1016/j.rser.2021.110861.

[14] Pan P, Sun Y, Yuan C, Yan X, Tang X. Research progress on ship power systems integrated with new energy sources: A review. Renew Sustain Energy Rev 2021;144. https://doi.org/10.1016/j.rser.2021.111048.

[15] Wang Z, Dong B, Wang Y, Li M, Liu H, Han F. Analysis and evaluation of fuel cell technologies for sustainable ship power: Energy efficiency and environmental impact. Energy Convers Manag X 2024;21:100482. https://doi.org/10.1016/j.ecmx.2023.100482.

[16] Xing H, Stuart C, Spence S, Chen H. Fuel cell power systems for maritime applications: Progress and perspectives. Sustain 2021;13:1–34. https://doi.org/10.3390/su13031213.

[17] Perna A, Minutillo M, Di Micco S, Cigolotti V, Pianese A. Ammonia as hydrogen carrier for realizing distributed on-site refueling stations implementing PEMFC technology. E3S Web Conf 2020. https://doi.org/10.1051/e3sconf/202019705001.

[18] Niermann M, Drünert S, Kaltschmitt M, Bonhoff K. Liquid organic hydrogen carriers (LOHCs)-techno-economic analysis of LOHCs in a defined process chain. Energy Environ Sci 2019;12:290–307. https://doi.org/10.1039/c8ee02700e.

[19] Bilgili L. Comparative assessment of alternative marine fuels in life cycle perspective. Renew Sustain Energy Rev 2021;144:110985. https://doi.org/10.1016/j.rser.2021.110985.

[20] McKinlay CJ, Turnock SR, Hudson DA. Route to zero emission shipping: Hydrogen, ammonia or methanol? Int J Hydrogen Energy 2021;46:28282–97. https://doi.org/10.1016/j.ijhydene.2021.06.066.

[21] Cai T, Zhao D, Ji L, Agarwal AK. Removal and mechanism analysis of NOx emissions in carbon-free ammonia combustion systems with a secondary fuel injection. Fuel 2023;344:128088. https://doi.org/10.1016/j.fuel.2023.128088.

[22] Cai T, Zhao D, Gutmark E. Overview of fundamental kinetic mechanisms and emission mitigation in ammonia combustion. Chem Eng J 2023;458:141391. https://doi.org/10.1016/j.cej.2023.141391.

[23] Gore K, Rigot-Müller P, Coughlan J. Cost assessment of alternative fuels for maritime transportation in Ireland. Transp Res Part D Transp Environ 2022;110:103416. https://doi.org/10.1016/j.trd.2022.103416.

[24] Shi J, Zhu Y, Feng Y, Yang J, Xia C. A prompt decarbonization pathway for shipping: green hydrogen, ammonia, and methanol production and utilization in marine engines. Atmosphere (Basel) 2023;14. https://doi.org/10.3390/atmos14030584.

[25] Sapra H, Stam J, Reurings J, van Biert L, van Sluijs W, de Vos P, et al. Integration of solid oxide fuel cell and internal combustion engine for maritime applications. Appl Energy 2021;281. https://doi.org/10.1016/j.apenergy.2020.115854.

[26] Afif A, Radenahmad N, Cheok Q, Shams S, Kim JH, Azad AK. Ammonia-fed fuel cells: A comprehensive review. Renew Sustain Energy Rev 2016;60:822–35. https://doi.org/10.1016/j.rser.2016.01.120.

[27] Cinti G, Discepoli G, Sisani E, Desideri U. SOFC operating with ammonia: Stack test and system analysis. Int J Hydrogen Energy 2016;41:13583–90. https://doi.org/10.1016/j.ijhydene.2016.06.070.

[28] Rivarolo M, Piccardo S, Montagna GN, Bellotti D. A multi-criteria approach for comparing alternative fuels and energy systems onboard ships. Energy Convers Manag X 2023;20:100460. https://doi.org/10.1016/j.ecmx.2023.100460.

[29] Seddiek IS, Ammar NR. Technical and eco-environmental analysis of blue/green ammonia-fueled RO/RO ships. Transp Res Part D Transp Environ 2023;114:103547. https://doi.org/10.1016/j.trd.2022.103547.

[30] Wu S, Miao B, Chan SH. Feasibility assessment of a container ship applying ammonia cracker-integrated solid oxide fuel cell technology. Int J Hydrogen Energy 2022;47:27166–76. https://doi.org/10.1016/j.ijhydene.2022.06.068.

[31] Ye M, Sharp P, Brandon N, Kucernak A. System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered

shipping. Int J Hydrogen Energy 2022;47:8565–84. https://doi.org/10.1016/j.ijhydene.2021.12.164.
[32] Perčić M, Vladimir N, Jovanović I, Koričan M. Application of fuel cells with zero-carbon fuels in short-sea shipping. Appl Energy 2022;309. https://doi.org/10.1016/j.apenergy.2021.118463.
[33] Kim K, Roh G, Kim W, Chun K. A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments. J Mar Sci Eng 2020. https://doi.org/10.3390/jmse8030183.
[34] Kim J. Modeling of proton exchange membrane fuel cell performance with an empirical equation. J Electrochem Soc 1995. https://doi.org/10.1149/1.2050072.
[35] Perna A, Minutillo M, Jannelli E, Cigolotti V, Nam SW, Han J. Design and performance assessment of a combined heat, hydrogen and power (CHHP) system based on ammonia-fueled SOFC. Appl Energy 2018;231:1216–29. https://doi.org/10.1016/j.apenergy.2018.09.138.
[36] Perna A, Minutillo M, Di Micco S, Di Trolio P, Jannelli E. Biogas and ammonia as hydrogen vectors for small refueling stations: Techno-economic assessment. AIP Conf Proc 2019;2191:02127. https://doi.org/10.1063/1.5138860.
[37] http://www.naviecapitani.it/gallerie%20navi/Containers/schede%20navi/A/Anna%20Sirkka.htm Accessed 01/03/2023 n.d.
[38] MakMed M43 Chttps://www.makmed.fr/en/moteurs/moteurs-mak/m43-propulsion/ Accessed 01/03/2023 n.d.
[39] Mak, Caterpillar. M 32 C Low Emission Engine 2009.
[40] Raucci C, Smith T, Dodds P. The potential of hydrogen to fuel international shipping. 2017.
[41] Industry B. Fuel cell power module for heavy duty motive applications. Burnaby: Ballard; 2016.
[42] Bloom Energy Energy Server 5 PRODUCT DATASHEET Always On. Bloom Energy Energy Server 5 PRODUCT DATASHEET Always On, Clean Energy Using Patented Solid Oxide Fuel Cell Technology n.d.
[43] The Linde Group. Ammonia linde tank https://www.linde-gas.com/en/images/linde-datasheet-01-ammonia-June-2017_tcm17-417364.pdf. Datasheet n.d.
[44] Guida D, Minutillo M. Design methodology for a PEM fuel cell power system in a more electrical aircraft. Appl Energy 2017;192:446–56. https://doi.org/10.1016/j.apenergy.2016.10.090.
[45] Elkafas AG, Rivarolo M, Gadducci E, Magistri L, Massardo AF. Fuel cell systems for maritime: A review of research development, commercial products, applications, and perspectives. Processes 2023;11. https://doi.org/10.3390/pr11010097.
[46] Cavo M, Gadducci E, Rivarolo M, Magistri L, Dellacasa A, Romanello M, et al. Thermal integration of PEM Fuel Cells and metal hydrides storage system for Zero Emission Ultimate Ship (ZEUS). E3S Web Conf 2022;334:04004. https://doi.org/10.1051/e3sconf/202233404004.
[47] Cavo MD analysis of P fuel cells and metal hydrides on a zero-emission ship: A model-based approach, Gadducci E, Rattazzi D, Rivarolo M, Magistri L. Dynamic analysis of PEM fuel cells and metal hydrides on a zero-emission ship: A model-based approach. Int J Hydrogen Energy 2021;46:32630–44. 10.1016/j.ijhydene.2021.07.104.
[48] Gadducci E, Lamberti T, Rivarolo M, Magistri L. Experimental campaign and assessment of a complete 240-kW Proton Exchange Membrane Fuel Cell power system for maritime applications. Int J Hydrogen Energy 2022;47:22545–58. https://doi.org/10.1016/j.ijhydene.2022.05.061.
[49] Chakraborty S, Dzielendziak AS, Köroğlu T, Yang K. Evaluation of smart eco - friendly public transport options in coastal cities: Towards a green future for the city of Southampton. vol. 2. 2013.
[50] Project, H.I. The Project. Available online: https://www.hyseas3.eu/the-project/ (accessed on 20 July 2022). n.d.
[51] HySeas III: The World's First Sea-Going Hydrogen-Powered Ferry—A Look at Its Technical Aspects, Market Perspectives and Environmental Impacts n.d.
[52] MARANDA Marine Application of a New Fuel Cell Powertrain Validated in Demanding Arctic Conditions. Available online: https://projectsites.vtt.fi/sites/maranda/ (accessed on 20 September 2022). n.d.
[53] German e4ships project reports on fuel cell maritime demos. Fuel Cells Bull 2016;2016:5. 10.1016/S1464-2859(16)30271-1.
[54] Advent Case Story: RiverCell. Available online: https://serene.advent.energy/cases/rivercell-serene-to-maritime/ (accessed on 12 October 2022). n.d.
[55] First fuel cell passenger ship unveiled in Hamburg. Fuel Cells Bull 2008;2008:4–5. 10.1016/S1464-2859(08)70372-9.
[56] Strazza C, Del Borghi A, Costamagna P, Traverso A, Santin M. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. Appl Energy 2010;87:1670–8. https://doi.org/10.1016/j.apenergy.2009.10.012.
[57] ShipFC, FIRST AMMONIA-POWERED FUEL CELL ON A VESSEL n.d. https://www.fch.europa.eu/news/major-fch-ju-funded-project-will-install-world's-first-ammonia-powered-fuel-cell-vessel.
[58] Valadez Huerta G, Álvarez Jordán J, Dragon M, Leites K, Kabelac S. Exergy analysis of the diesel pre-reforming solid oxide fuel cell system with anode off-gas recycling in the SchIBZ project. Part I: Modeling and validation. Int J Hydrogen Energy 2018;43:16684–93. https://doi.org/10.1016/j.ijhydene.2018.04.216.
[59] Louvros P, Trivyza NL, Komianos A, Boulougouris E. Fuel cell, ammonia powered container ship: A case study. Transp Res Procedia 2023;72:2245–52. https://doi.org/10.1016/j.trpro.2023.11.713.
[60] Duong PA, Ryu BR, Lee H, Kang H. Thermodynamic analysis of integrated ammonia fuel cells system for maritime application. Energy Rep 2023;10:1521–37. https://doi.org/10.1016/j.egyr.2023.08.028.
[61] Park Y-A, Medda F. Hub Status and Indexation of Container Ports. Asian J Shipp Logist 2015;31:253–72. https://doi.org/10.1016/j.ajsl.2015.06.005.
[62] UNCTAD. Review of Maritime Transport 2021 - Chapter 3: Freight rates, maritime transport costs and their impact on prices 2021.
[63] Kawamoto R, Mochizuki H, Moriguchi Y, Nakano T, Motohashi M, Sakai Y, et al. Estimation of CO_2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA. Sustain 2019;11. https://doi.org/10.3390/su11092690.