

System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping

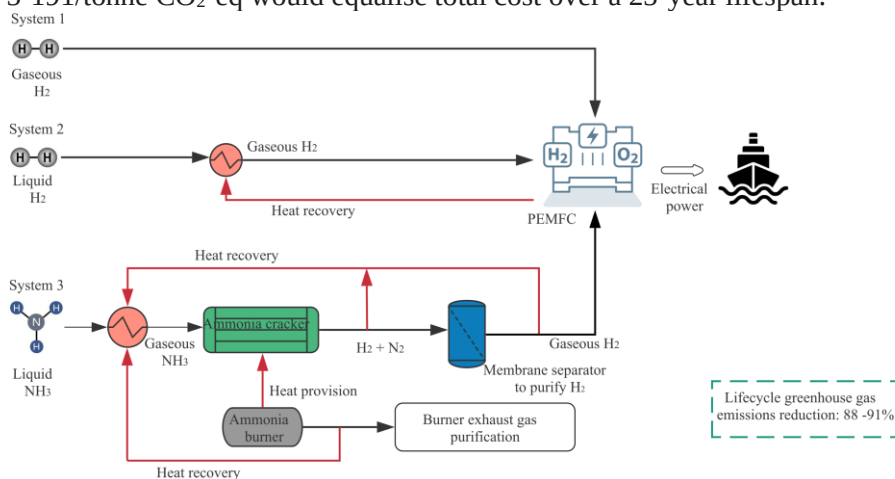
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Abstract

With the aim to reduce emissions from marine transport, electric propulsion systems for a water taxi and container ship powered by a hydrogen polymer electrolyte membrane fuel cell system are designed and analysed compared to the current fuel-oil engine systems in terms of system energy and exergy efficiency, fuel consumption, mass and volume, environmental impacts and cost. Hydrogen is stored either as a compressed gas (GH_2), cryogenic liquid (LH_2) or produced from liquid ammonia (LNH_3) and can deliver 91%, 91% and 88% greenhouse gas reductions, respectively. All hydrogen sources fit within ship volume and mass constraints apart from GH_2 in the cargo ship. In the absence of carbon policy measures, the costs over a 25-year system life are 108% (GH_2), 112% (LH_2), 116% (LNH_3) greater for the container ship and 43% (GH_2), 105% (LNH_3) greater for the water taxi. A carbon tax of £75-191/tonne CO_2 -eq would equalise total cost over a 25-year lifespan.



Keywords: Ammonia; Hydrogen; Fuel cell; Marine transport; System design; Thermodynamic analysis

1. Introduction

Ships emit significant amounts of pollutants, including nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM) and carbon dioxide (CO_2), to the atmosphere, which poses threats to human

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health and leads to acid rain and global warming. According to the study by VIKI (2019) and the study published by Sofiev et al. (2018), the SO_x, NO_x and CO₂ emissions from marine traffic accounts for about 13%, 15% and 2.5% of the global emissions respectively [1], [2]. As global population grows, so does the maritime trade, and carbon dioxide emissions from the sector are expected to grow up to 250% by 2050 if no measure is taken [3].

To mitigate the emission problems, the International Maritime Organization(IMO) have adopted some regulations and strategies. IMO's MARPOL Annex VI states that from 1 January 2020, all the ships sailing in Emissions Control Areas (ECAs) can only use fuels with sulfur content lower than 0.1% m/m (mass/mass) [4]. For ships outside ECAS, the sulfur cap is 0.5% m/m [4]. Based on the IMO's NO_x Tier III standard, the NO_x emission limit is 2.0 -3.4 g/kWh for all new ships constructed after 1 January 2016 and sailing in the North American ECA and United States Caribbean Sea ECA, or constructed after 1 January 2021 and sailing in the Baltic Sea ECA and the North Sea ECA [5]. IMO implements measures toward carbon dioxide emission as well, such as Energy Efficient Design. By 2050, the IMO aims to reduce the total annual greenhouse gas (GHG) emissions from international shipping by 50% compared with the 2008 level [3].

Different options can be taken to reduce the shipping emissions, such as installing a scrubber to reduce SO_x emission and selective catalytic reduction (SCR) reactor to remove NO_x. Modifying the internal combustion engine (ICE) or completely changing the internal combustion propulsion system to the electric battery or fuel cell propulsion system can also reduce emissions. Using alternative fuel is another option. Ship owners can switch from Marine diesel oil (MDO) or heavy fuel oil (HFO) to marine gas oil (MGO), ultra-low sulfur fuel oil (ULSFO, fuel oil with sulfur content lower than 0.1 mass%), liquified natural gas (LNG), biofuels, hydrogen and ammonia etc. Examples of different possible fuels and their volumetric and gravimetric properties are provided in Table 1.

Table 1- Heating values of different fuels [6]–[10].

	Higher heating value		Lower heating value		Density kg/m ³
	10 ⁶ J/kg	10 ⁹ J/m ³	10 ⁶ J/kg	10 ⁹ J/m ³	
HFO	41.8	41	39	38.2	980
ULSFO	-	-	42	38.2	910
MGO/LSMGO	45.9	39.2	42.7	36.5	855
MDO	43	39	41	37	900
Compressed hydrogen gas (288.15 K, 350 bar)	142	3.3	120	2.8	23.7
Compressed hydrogen gas (288.15 K, 700 bar)	142	5.4	120	4.6	38
Liquified hydrogen (20.28 K, 1 atm)	142	10	120	8.7	72.4
Liquified ammonia (240.15 K, 1 atm)	22.5	15.3	18.6	12.7	683
Liquified ammonia (298.15K, 10bar)	22.5	13.7	18.6	11.3	603

HFO: heavy fuel oil; ULSFO: ultra-low sulfur fuel oil (0.1 mass % S); MGO: marine gasoil; LSMGO: low-sulfur marine gasoil (0.1 mass % S); MDO: marine diesel oil.

Among all these options, both hydrogen and ammonia fuel, have attracted increasing interest as zero carbon fuels due to their possibility to achieve zero emissions if generated from renewable sources, and can offer high power generation efficiency when utilised in fuel cell propulsion systems. Hydrogen is a carbon-free fuel with high mass energy density. It can be directly utilised in polymer electrolyte membrane fuel cells (PEMFCs). There have been several projects using hydrogen fuel cells on ships. For example, the MEMO H2 project by Alewijnse Marine Systems etc. successfully constructed and operated a PEMFC (60 kW) and battery hybrid ferry for 100 passengers [11].

However, hydrogen still faces many issues, such as the low volumetric energy density and storage issues. To reduce the volume of hydrogen storage, the hydrogen is usually stored as high pressure compressed gas at 350 bar or 700 bar at 293.15 K or as liquid at 20.28 K under atmospheric pressure [12]. Safety is another issue. Hydrogen is highly flammable and easy to escape without attention. Ammonia is a hydrogen-carrier with a high hydrogen content. In contrast with hydrogen, ammonia has higher volumetric energy density and is easier to handle and store. According to the study by Valera-Medina et al. , ammonia can reduce the storage cost by at least three times compared with hydrogen[13]. Another advantage of ammonia over hydrogen is the mature supply chain and an existing infrastructure owing to the fertilizer industry. Moreover, ammonia has low fire and explosion risks[13]. However, the conversion between hydrogen and ammonia carries an energy penalty. There are already some studies working on reducing the energy requirement of the ammonia synthesis process. For example, Wijayanta and Aziz proposed an integrated system to convert algae to ammonia at energy efficiency of 38% [14]. Safety is another concern of ammonia due to its toxicity but well established measures already exist in place to handle it [15].

There are many studies that investigate the potential application of ammonia in transportation, including ammonia used in internal combustion engines (ICEs) and in fuel cells. Reiter and Kong [16] established a study to investigate the characteristics of the ammonia-diesel dual fuel compression ignition (CI) engine. The study shows that the ammonia dual fuel engine can reduce NO_x emissions compared with the diesel engine if less than 40% of the energy is supplied by ammonia, but that the ammonia emission by the diesel-ammonia dual fuel engine might reach 1000 to 3000 ppmv depending on the ammonia fueling rate. This ammonia emission level was higher than the U.S. Occupational Safety and Health Administration (OSHA) exposure limit of 50 ppmv. MAN Energy Solutions reported that the application of ammonia in two-stroke dual fuel engine could reduce SO_x , PM and CO_2 emission by around 90% and it has a plan to install the first two-stroke ammonia dual fuel engine in 2024 [17] [18]. Ezzat and Dincer introduced and thermodynamically analyzed a vehicular system powered by hydrogen-ammonia ICE integrated with thermoelectric generator and ammonia electrolyte cell[19]. The designed systems had energy and exergy efficiencies of 31.1% and 28.94%, respectively.

As well as its use in ICEs, ammonia has been applied in onboard fuel cells – an area drawing increasing interest. Zhao et al. [20] conducted a technoeconomic analysis over several carbon-neutral transport fuels and concluded that green ammonia could be 31% cheaper than green hydrogen on a source-to-tank basis. With this result, they then conducted an experimental study to investigate the performance of a hydroxide exchange membrane direct ammonia fuel cell with a precious-metal-free catalyst. Al-Hamed and Dincer proposed and thermodynamically analyzed a 3100kW-locomotives power system based on the ammonia solid oxide fuel cell and gas turbine (SOFC-GT) integrated with an ammonia dissociation and separation unit (ADSU) and PEMFCs[21]. They concluded that the ADSU-PEMFC integrated SOFC-GT system could reach overall energy and exergy efficiency of 61.2% and 66.3%, which were 13% and 10% higher than that of the simple SOFC-GT system. Kim et al. analyzed and compared different ammonia systems, including ICE, ammonia cracker with PEMFC, and solid oxide fuel cell (SOFC) for ship propulsion[6]. Based on the study, the SOFC system was the most environmentally friendly but was the most expensive and had the lowest power density and dynamic response. Chu et al. proposed an extended-range design for electric vehicles based on the ammonia electrolysis and PEMFC, then the application of the design on a trunk case study was analysed[22]. Ezzat and Dincer introduced and conducted energy and exergy analysis for

two liquid ammonia power systems for vehicles [15]. The first system is powered by the ADSU and ICE and the second system is powered by the ADSU and PEMFC supplemented with ICE. In their other study [23], an exergoeconomic analysis of the designed ADSU and PEMFC with ICE system for a 118kW vehicle was conducted and the overall exergy efficiency and the cost rate of the system were found to be 36.2% and 29.16 £/hr. Other researchers have focussed on the onboard hydrogen production from ammonia for PEMFCs. Wang et al. developed a miniature ammonia cracker with CeO₂-promoted Ni/Al₂O₃ catalysts for portable hydrogen fuel cells. The ammonia cracker developed, which has a weight of 195g and a volume of 50cm³, could reach ammonia conversion of 99.9% at 600 °C and produce H₂ equivalent to 158W fuel cell power output at an ammonia feed rate of 1100 sccm [24]. Pochari Technologies invented a commercial ammonia cracker with Cs promoted Ru/CNT catalyst for vehicular applications, which could crack ammonia at a flow rate of 12kg/hr and the ammonia conversion can reach 99.95% at 600°C [25]. Hunter et al. experimentally demonstrated a system consisting of a lithium imide ammonia cracker and an anhydrous MgCl₂ gas purification device to power a 100 kW PEMFC stack [26]. CSIRO developed a Ru/Al₂O₃ catalyzed ammonia cracker and Pd-V separation membrane (0.3 m² membrane area) integrated system, which can produce hydrogen at a rate of 15 kg/day and with an outlet ammonia concentration lower than 10 ppbv and nitrogen concentration lower than 1 ppmv [27]. Van Hassel et al. conducted an experimental study to prepare and characterize ammonia sorbents made by metal chlorides on activated carbons, which was used to purify hydrogen onboard and could reduce the ammonia concentration from 500 ppmv to under 0.1 ppmv [28].

The motivation of this study is to undertake a design and analysis study of a marine propulsion system that does not have any harmful impacts on the environment. Based on the literature [6], [15]–[23], compared with the hydrogen or ammonia internal combustion engine, the hydrogen or ammonia fuel cells can offer greener, more efficient and silent operation. Therefore, this study will focus on the marine fuel cell system, and mainly on the marine PEMFC system due to its relatively high technical and commercial maturity in mobile applications. To the best of the author's knowledge, most of the studies about onboard ammonia application in PEMFCs have focussed on experimental investigations of the ammonia decomposition and purification technology to produce hydrogen for PEMFCs [24]–[28]. There are only a few system design studies [15], [22], [23], and most of these are about PEMFCs with ICE or battery for vehicular application and they mainly focussed on a thermodynamic analysis. None of them provide detailed system design and comprehensive performance analysis of the ammonia decomposition and PEMFC system, specific for marine transport at different scales, which could provide insight into the feasibility and competitiveness of hydrogen compared to ammonia as a fuel in marine transport.

In this study, a clean ammonia marine propulsion system consisting of an ammonia cracking unit and PEMFC is introduced and analyzed thermodynamically. Gaseous and liquid hydrogen fuelled PEMFC marine propulsion system, are also studied, and compared to the ammonia option.

The specific objectives for the study are listed below:

- To design an ammonia cracker plus PEMFC system, a gaseous hydrogen PEMFC system and a liquid hydrogen PEMFC system suitable for ships at different scale.
- To build scalable thermodynamic models for the designed hydrogen systems and liquid ammonia system.
- To apply the thermodynamic models on two case studies - 12-passenger water taxi and 2600 twenty-

foot equivalent unit (TEU) container ship, respectively.

And based on the results, assess the performance of the hydrogen and ammonia systems for the two case studies with respect to the following performance indicators: fuel consumption, system energy and exergy efficiency (include exergy destruction rate analysis), mass and volume, environmental impact, and cost. The performance of the conventional marine engine and ammonia-fuel oil dual fuel engine from literature are used as base-cases for comparison to the designed hydrogen and ammonia fuel cell systems. The ammonia dual fuel engine system requires the use of some diesel to provide 5%-45% of the engine power depending on the ship scale and load factor [16], [29]–[34].

2. System description

This section describes the proposed liquid ammonia (LNH_3) PEMFC power system, gaseous hydrogen (GH_2) PEMFC power system, and liquid hydrogen (LH_2) PEMFC power system. As shown in Figure 1, all the three systems are powered by PEMFC, but they have different fuel provision units.

2.1 Fuel provision unit

This subsection introduces the fuel provision unit of the GH_2 PEMFC system, LH_2 PEMFC system and LNH_3 PEMFC system separately.

2.1.1 GH_2 PEMFC system fuel provision unit

The fuel for the GH_2 PEMFC system is the hydrogen gas stored in the compressed gas tank at 350bar and 288.15 K as seen in Figure 1. The hydrogen from the tank enters the pressure regulation valves to reduce the pressure to 120kPa before feeding to the PEMFC unit.

2.1.2 LH_2 PEMFC system fuel provision unit

The LH_2 PEMFC system works similarly to the GH_2 PEMFC system, except that the fuel used is the cryogenic liquid hydrogen stored at 20.28K and 101.325kPa as shown in Figure 1. The liquid hydrogen is evaporated through a heat exchanger, which uses the waste heat from the fuel cell as the heat source, before feeding to the PEMFC unit. Due to the heat transfer from the surrounding to the cryogenic hydrogen tank, the liquid hydrogen will continuously evaporate with a boil-off ratio of around 1%/day [35]. The boil-off hydrogen gas can be controlled by a valve and directed to the fuel cell as shown in Figure 1.

Both GH_2 and LH_2 have the potential to be applied as marine fuels. Liquid hydrogen has higher volumetric energy density than gaseous hydrogen, but the compressed hydrogen gas storage is more popular than the cryogenic liquid hydrogen storage in the area of transportation because of the decent reliability, reasonable efficiency and technological simplicity[36]. In this study, the liquid hydrogen system is only considered for the case where the onboard space is not sufficient for the GH_2 tanks.

PEMFC unit: all of the GH₂ PEMFC system, LH₂ PEMFC system and LNH₃ PEMFC system are powered by PEMFC

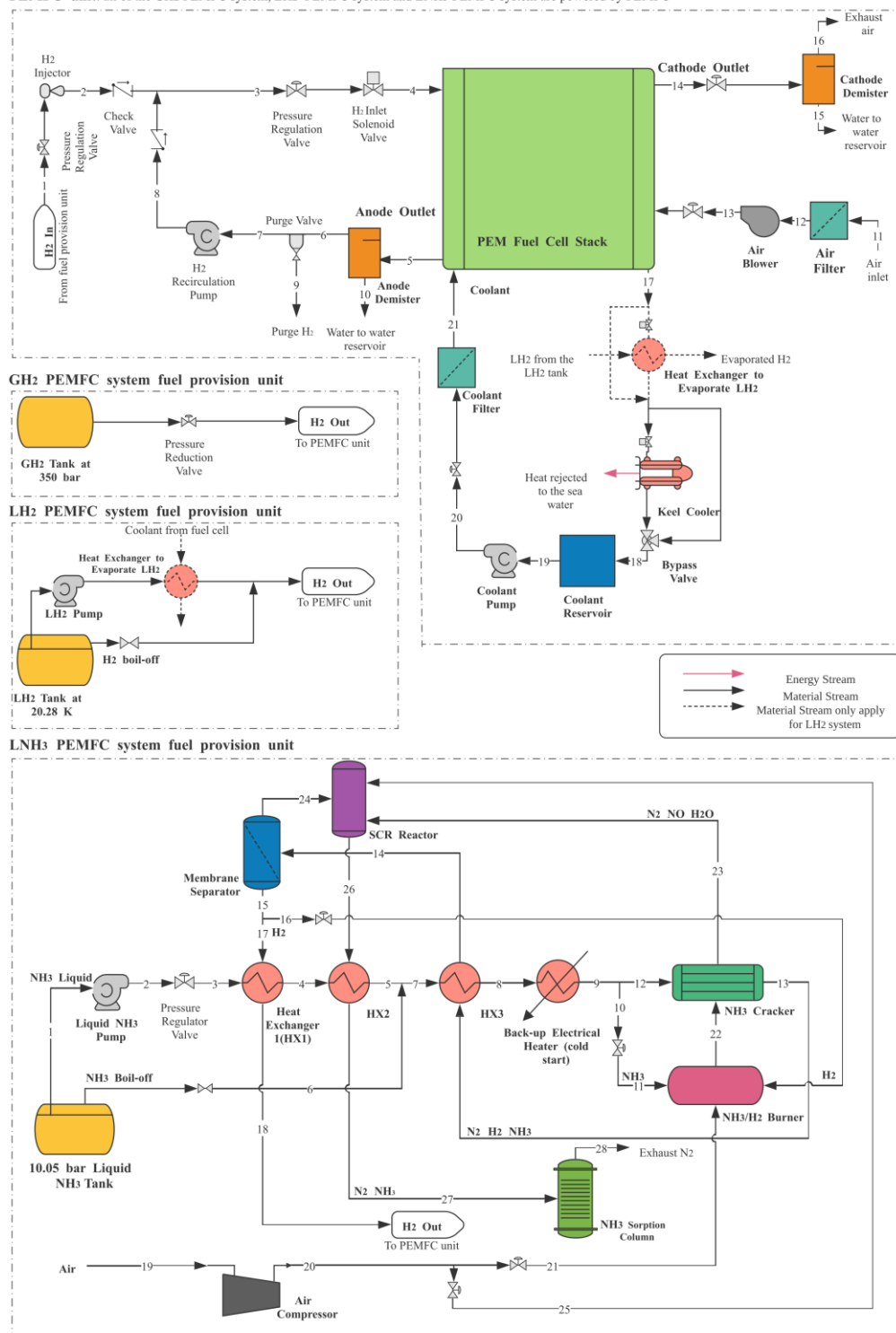
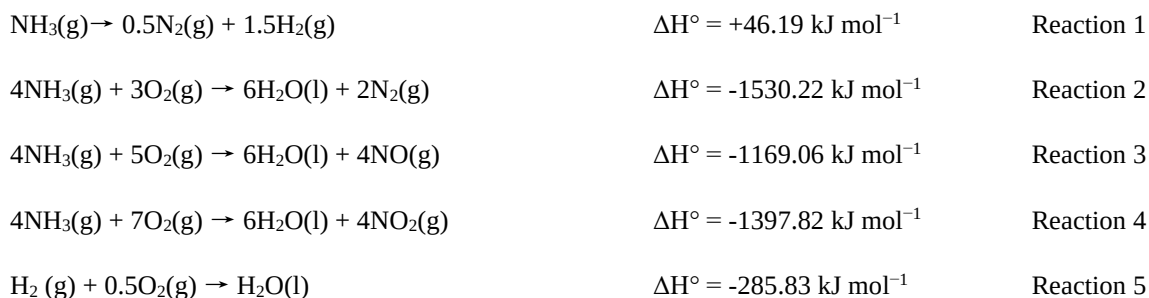


Figure 1- Simplified flow diagram of the GH₂ PEMFC system, LH₂ PEMFC system and LNH₃ PEMFC system

2.1.3 LNH₃ PEMFC system fuel provision unit

The fuel provision unit of the LNH₃ PEMFC system is more complicated than the H₂ PEMFC systems as shown in the lower section (LNH₃ PEMFC system fuel provision unit) of Figure 1 with operating conditions provided in Table 2. The liquid ammonia fuel of the system is stored at 1005kPa and 298.15K in the stainless-steel tank. As with the liquid hydrogen tank, the ammonia tank experiences a boil-off ratio of 0.04%/day and the boil-off gas can be directed to the fuel cells. A Mag-drive ammonia pump is used to pump the ammonia liquid out of the tank. Then a pressure regulation valve is used to reduce the pressure of the ammonia liquid to 350kPa. The liquid ammonia is partially evaporated after the valve. Three heat exchangers (HX1, HX2, HX3) are applied to further evaporate and heat up the ammonia by using the hot stream after the ammonia cracker and burner. Ammonia cracking (Reaction 1) is an endothermic reaction, therefore, part of the ammonia fuel from the fuel tank (stream 11) and hydrogen produced from the cracker (stream 16) is combusted in the burner to provide sufficient heat to the cracker. The ammonia to hydrogen volume ratio to the burner (Reaction 2 - 5) is assumed to be 1.5. The high temperature outlet stream (stream 22) from the burner then goes through the ammonia cracker and provides heat to the cracker. The burner is surrounded by a 3cm Morgan ceramic fibre insulator with thermal conductivity of 0.44 W/m K to prevent heat loss [37]. Unlike the LH₂ PEMFC system, where part of the waste heat from the fuel cells is reused to evaporate the liquid hydrogen, the fuel cell waste heat is discarded in the LNH₃ PEMFC system. Because if the low-grade fuel cell heat is reused in the LNH₃ system, the medium-grade heat from the membrane separator or SCR reactor cannot be utilized due to the temperature restriction of the heat exchangers. Additional electrical cooling would then be required to cool down the outlet stream from the separator or SCR reactor to meet the operational temperature of the fuel cell or ammonia sorption column, which occupies extra space and consumes extra energy that outweighs the energy saved by reusing the fuel cell waste heat.



The ammonia cracker produces output (stream 13) of around 75 vol% hydrogen, 25 vol% nitrogen and 250-500ppmv trace ammonia[24], [38]. According to ISO 14687-2, the ammonia concentration and nitrogen concentration for the PEMFC in the fuel cell vehicle should be lower than 100ppbv and 100ppmv, respectively [39]. A palladium membrane separator is used to purify the hydrogen from the cracker. After the membrane separator, the nitrogen and ammonia concentration in the hydrogen stream (stream 15) are reduced to 1ppmv and 10ppbv, respectively and can be fed to the PEMFC to generate power [40].

In order to achieve low emissions from the system, a vanadium pentoxide (V₂O₅) selective catalytic reactor is used to remove the NO_x produced by the ammonia burner. Part of the unreacted ammonia from the cracker (stream 24) is used as the reactant for NO_x removal in the SCR (Reaction 6 - 7). The NO_x conversion of the SCR can reach 90% but the ammonia slip from the SCR is around 120ppmv

[41], [42]. An ammonia sorption column with Calgon Carbon Ammonasorb™, which is a phosphoric-acid-impregnated activated carbon based sorbent, is applied to lower the ammonia concentration to 0.1 ppmv in the outlet (point 28) [25].



Table 2-Operating condition of the main components in the LN_{H3} PEMFC system fuel provision unit[24], [27], [38], [41]–[45]

Equipment	Operating temperature K	Operating pressure 10 ³ Pa	Conversion
Ru/Al ₂ O ₃ ammonia cracker for water taxi	873.15	350	99.95%
Ni/Al ₂ O ₃ ammonia cracker for cargo ship	873.15	350	99.9%
Ammonia/hydrogen Burner	1873.15-1973.15	205	Concentration in the outlet: 30ppmv H ₂ 400ppmv NO;0.2ppmv NO ₂ ;85ppmv NH ₃
Membrane separator	623.15	343	-
SCR reactor	533.15	205	90%

2.2 PEMFC unit

All three systems are powered by PEMFCs (PEMFC unit) as shown in Figure 1. In the PEMFC unit, the hydrogen from the fuel provision unit is fed to the fuel cell with a stoichiometric ratio of 1.2 to prevent anode starvation. To increase hydrogen utilization, the unused hydrogen (stream 5 in the PEMFC unit) is recirculated back to the anode by the hydrogen recirculation pump. The water droplets in the anode outlet at point 5 are eliminated by the anode demister and a dynamic purge valve is used to prevent the build-up of impurities and inert gases at the anode. At the cathode, air at the atmospheric condition (298.15K, 101.325kPa) is delivered to the fuel cell at a stoichiometric ratio of 2 after purification by an air filter.

The PEM stack operates at 328.15K and 110kPa to 120kPa. Although PEMFCs operate at relatively high efficiency (40%–65%), a significant amount of waste heat is released. De-ionized Water (DI H₂O) is used as the coolant and fed to the fuel cell (stream 21) at a temperature of 323.15K to 338.15K [46]. The coolant removes the stack waste heat and flows out of the stack (stream 17) at the temperature of 323.15K to 348.15K [46]. The hot coolant outlet from the stack is cooled by a keel cooler, which works like a heat exchanger and uses the bulk seawater to cool down the hot stream. The cooling rate can be controlled by the coolant pump and the coolant inlet temperature to the fuel cell can be controlled by the 3-way bypass valve. Compared with the air radiator and fan used in the conventional land vehicle PEMFC system, the seawater keel cooler has better heat transfer characteristics because of the higher heat capacity of the water than the air. The more-efficient heat transfer results in smaller size of the keel cooler than the radiator.

3. Case studies

Two case studies, a 12-passenger water taxi and a 2600 TEU container ship, are considered in this study.

3.1 12-passenger water taxi

Water taxi services have expanded quickly in recent years. To reduce the transportation emissions

and provide a quieter experience to passengers, there is an increasing trend of moving from internal combustion engine powered water taxis to cleaner electric powered boats. Hence, a typical 12-passenger water taxi is used as a case study.

The specification and the load profile of a typical 12-passenger water taxi are shown in Table 3 and Table 4. The water taxi has a full propulsion load of 25kW and runs at full load for 75% of its service time. Except for the propulsion load, the power system must be able to provide the hotel load (e.g. lighting loads) for the boat. In the conventional diesel engine system, the propulsion load is provided by a diesel engine while the hotel load can be supplied by an alternator and a battery. For the designed hydrogen or ammonia systems, both propulsion and hotel loads are provided by the fuel cells or the back-up battery. The water taxi is assumed to operate for 8 hours per day and 320 days per year. If the water taxi can be refilled every day, the systems designed must at least be able to operate continuously for 8 hours.

Table 3- Ship specification of the 12-passenger water taxi [47], [48] and feeder container ship [49], [50]

	Water taxi	Feeder container ship
Capacity	12 passengers	2600 TEU
Deadweight, max/tonne	3.25	33000
Design draught/m	1	11.4
Length overall/m	10	200
Breadth/m	4	29.8
Rated shaft power/kW	25	21770
Average speed/knot	13.5	22

TEU: twenty-foot equivalent-unit

Table 4- Load profile of the 12-passenger water taxi [51] and feeder container ship [49]

Water taxi				Feeder container ship			
Propulsion load factor	Propulsion Power (10^3 W)	Auxiliary Power (10^3 W)	Time spent (%)	Propulsion load factor	Propulsion Power (10^3 W)	Auxiliary Power (10^3 W)	Time spent (%)
100%	25	0.8	75%	100%	21770	700	1%
15%	3.75	0.8	25%	65%	14150.5	700	32%
				55%	11973.5	700	15%
				35%	7619.5	700	24%
				25%	5442.5	700	15%
				15%	3265.5	700	10%
				5%(manoeuvring)	1088.5	1700	1.75%
				2%(Idle)	435.4	600	1.25%

The overview diagram of the 12-passenger water taxi system consisting of the main power unit and the electrical circuit is shown in Figure 2 (a). The power is assumed to be provided by the Hydrogenics HyPM HD-30 fuel cell stack with rated power of 31kW. A battery is used to assist the fuel cell stack when the stack is insufficient for power supply and to provide the start-up power for the PEMFC and the ammonia cracker. The start-up time of the PEMFC is below 15s at 293.15K and that for the cracker is around 10 mins [25], [52]. According to the studies [25], [53], [54], the PEMFC and ammonia cracker could provide sufficient load response without the aid of the energy storage system.

The fuel cell stack output voltage is in the range of 60 – 120 V_{DC} [46]. A converter is used to boost the voltage from the fuel cell to 250 – 350 V_{DC} , which can be supplied to the motor propulsion system. The water taxi is assumed to operate on a 12/24 V_{DC} onboard electrical system for the hotel power.

Therefore, a DC/DC converter is applied to convert the 250-350 V_{DC} power to 12/24 V_{DC}.

3.2 2600TEU container ship

The container ships, which transport around 90% of the non-bulk goods globally, contributes significantly to the marine traffic emissions [55]. About 56% of the existing container ships are feeder container ships with capacity of below 3000TEU and these feeder container ships account for about 65% of the total container ships' emissions in the ECAs [2]. As a result, a typical 2600TEU feeder container ship is chosen as another case study.

The specification of a typical 2600TEU container ship and the load profile at sea and at berth are shown in Table 3 and Table 4. The 2600TEU container ship is originally powered by a diesel engine for propulsion and two diesel gensets with 1800kW each for auxiliary power [49]. The auxiliary power includes the electric hotel loads onboard and loads for manoeuvring. The average hotel load for the feeder container is assumed as 700kW at sea [49]. In addition to the hotel loads, extra manoeuvring power of about 1000kW is required for situations such as port-in/out [54]. The ship is assumed to be at sea for 75% of time per year (273 days). For the rest of the time, the ship is at berth, when the main engine stops working, but the auxiliary engines are still on to supply the necessary auxiliary power, such as the power for cargo operations. The total auxiliary power required at berth is assumed as 650 kW [56].

In this case study, the ammonia and hydrogen electric propulsion systems are applied on the target 2600TEU cargo ship that travels across the Pacific Ocean (PRD–SPB corridor) with a nonstop voyage leg of 6,600nm[50].

(a) Water Taxi Electrical System

DC/DC Charger

Emergency and Start-up Battery

To equipment

250-350 Vdc

DC/DC Battery Charger

BMS

Battery

DC/DC Converter

12/24 Vdc

Motor Controller

M

Hotel power, e.g. power for lightings and radio

Auxiliary power for equipments e.g. for fuel cell and air delivery

GH2 from the hydrogen tank (GH2 PEMFC system)

Evaporated LH2 from the LH2 evaporator (LH2 PEMFC system)

H2 from the ammonia cracker (LNH3 PEMFC system)

60-120 Vdc

Purge H₂

Demister

Water to water reservoir

31kW Hydrogen Fuel Cell Stack

Anode Outlet

Cathode Outlet

Exhaust air

Water to water reservoir

Blower

Air Filter

Air inlet

LH2 Evaporator

Keel Cooler

Heat rejected

Coolant Pump

Coolant Reservoir

Legend:

- Thermal (Red arrow)
- Electricity (Blue arrow)
- Material (Black arrow)

(b) Cargo Ship Electrical System

The diagram illustrates the 690V DC Bus system and the detailed components of a 198kW Fuel Cell Stack (FC stack a).

690V DC Bus System:

- Power Sources:** Battery/BMS, 198kW Fuel Cell Stacks (FC stack a, b, etc.), DC/AC Inverter, and Transformer.
- DC/DC Converters:** Multiple converters are connected to the bus, receiving input from the fuel cell stacks and the battery/BMS.
- Outputs from the Bus:**
 - Auxiliary Load
 - Drive units (connected to Motors and Gear Boxes)
 - Thruster

198kW Fuel Cell Stack (FC stack a) Details:

- Hydrogen System:** Hydrogen fuel is supplied to the stack from a hydrogen tank (GH2 PEMFC system) and an ammonia cracker (LNH3 PEMFC system). The system includes a purge H2 line and a demister for anode outlet water.
- Air System:** Air is supplied to the stack from an air inlet, passing through a blower and an air filter. The system includes a demister for cathode outlet water and a blower for air inlet to the stack.
- Cooling System:** The stack has an outlet coolant line to a keel cooler, which rejects heat to the water reservoir. The coolant is then pumped back to the stack via a coolant pump and reservoir.
- Other Components:** The stack includes an LH2 evaporator, a demister, and a blower for air inlet to the stack.

Figure 2-Electrical system of a) Water taxi and b) Cargo ship

Figure 2 (b) presents the overview diagram of the 2600 TEU container ship electric system. The propulsion and auxiliary power for the container ship are assumed to be provided by a number of Hydrogenics HyPM HD-180 fuel cell stacks with continuous power of 198 kW. The container ship is assumed to run on a DC system with 690V main DC bus. The Hydrogenics HD-180 fuel cell stacks, which provide voltage of 180 to 360 V_{DC}, are connected in parallel to the 690V DC bus through DC-DC converters. This architecture makes sure that the fuel cell stacks can be controlled independently and can provide redundancy for the system.

The DC bus can supply voltage to the variable frequency drives (VFD), which are used to drive and control the electric motors. The motors convert the electrical power to mechanical power for the two propellers or the transverse thruster. The propellers are the main source for the ship's propulsion and the thruster is used for manoeuvring. The equipment for the power system, such as compressors and pumps, and the onboard appliances, such as lights, usually require AC voltage (e.g. 110V_{AC} or 220V_{AC}). Hence, DC-AC inverters and transformers are used to convert the 690V voltage from the DC bus before supplying to the onboard devices.

4. System Analysis

4.1 Thermodynamic Model

Thermodynamic models are developed to analyse the introduced hydrogen and ammonia systems, which could identify and determine the mass flow rates, enthalpies, exergies, pressures and temperatures of the flows entering and leaving the systems to meet the power requirement of the ship.

The assumptions of the thermodynamic model are listed below:

- The reference temperature and pressure are 298.15K and 1 atm.
- All processes are assumed steady state.
- The blower, compressor and pump are assumed as adiabatic equipment with negligible kinetic energy and potential energy.
- The gases in the system are assumed as ideal gases.
- The heat loss of the heat exchangers is neglected.
- The activation loss and concentration loss of the fuel cell stacks are dominated by the cathode.

According to the first law and second law of thermodynamics, the mass balance (1), energy balance (2) and exergy balance (4) for steady-state processes can be expressed as follow,

$$\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i \quad (1)$$

$$\dot{Q} - \dot{W} = \Delta \dot{E}_{KE} + \Delta \dot{E}_{PE} + \Delta \dot{H} \quad (2)$$

$$\Delta \dot{H} = \dot{H}_{out} - \dot{H}_{in} = \sum_{out} \dot{n}_i \widehat{H}_i - \sum_{in} \dot{n}_i \widehat{H}_i \quad (3)$$

$$\dot{Q} \left(1 - \frac{T_0}{T}\right) + \sum_{in} \dot{m}_i ex_i = \sum_{out} \dot{m}_i ex_i + \dot{W} + \dot{E}_{Xd} \quad (4)$$

The detail of the mass, energy and exergy balance of the main components and the parameters ([24], [27], [38], [41]–[46], [57]–[60]) used are provided in the supplementary material A.

4.1.1 Power Demand

This subsection analyses the power required to be generated by the fuel cell stack to meet the propulsion and auxiliary power requirements.

The power given by the fuel cell stacks should cover the main propulsion power ($PWR_{propulsion\ shaft}$), and auxiliary power ($PWR_{auxiliary}$). The auxiliary power includes the hotel loads (PWR_{hotel}), additional power for manoeuvring ($PWR_{manoeuvring}$) if any, and the power for the equipment ($PWR_{power\ equipment}$) in the power generation system, such as the pumps, controller, and sensor. The power required for the controller and sensor are assumed as 200W for the water taxi PEMFC system and 175 kW for the cargo ship PEMFC system (if all stacks are at work) [46]. In some cases, when the fuel cell power is insufficient, the battery can be used to assist the fuel cell stack for auxiliary power provision.

After considering the electrical system (Figure 2) and the electrical efficiencies (η) (Table 5), the required power produced by the stacks (and battery) for the water taxi and cargo ship systems can be expressed as,

$$PWR_{water\ taxi} = \frac{PWR_{propulsion\ shaft, water\ taxi}}{\eta_{converter} \cdot \eta_{motor} \cdot \eta_{motor\ controller}} + \frac{PWR_{hotel, water\ taxi}}{\eta_{converter} \cdot \eta_{converter}} + \frac{PWR_{power\ equipment, water\ taxi}}{\eta_{converter} \cdot \eta_{converter}} \quad (5)$$

$$PWR_{cargo\ ship} = \frac{PWR_{propulsion\ shaft, cargo\ ship}}{\eta_{converter} \cdot \eta_{motor} \cdot \eta_{drive} \cdot \eta_{gearbox}} + \frac{PWR_{thruster}}{\eta_{converter} \cdot \eta_{motor} \cdot \eta_{drive}} + \frac{PWR_{hotel, cargo\ ship} + PWR_{power\ equipment, cargo\ ship}}{\eta_{converter} \cdot \eta_{inverter} \cdot \eta_{transformer}} \quad (6)$$

Table 5-Efficiencies for the main electrical components[6], [61]

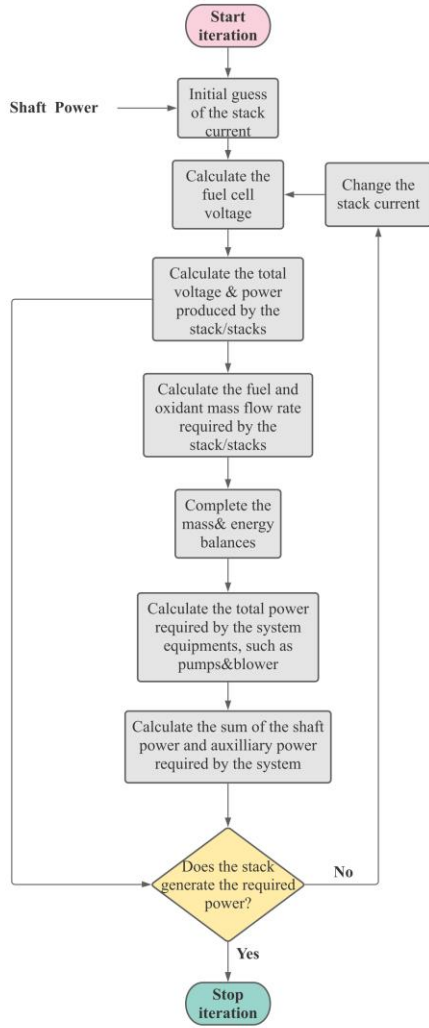
Electrical Components	Efficiency (η)
Converter/Inverter	97%
Motor	96%
Transformer	95%
Gearbox	94%
Motor controller/Drive	97%
Battery (include battery charger)	91%

The detailed calculation of the power given by the fuel cell stacks and the parameters ([46], [57], [62]–[64]) used are provided in the supplementary material B.

4.1.2 Model block

The system model structure of the designed hydrogen systems and ammonia system are summarized in Figure 3.

(a) GH2 or LH2 PEMFC System Model Block



(b) LNH3 PEMFC System Model Block

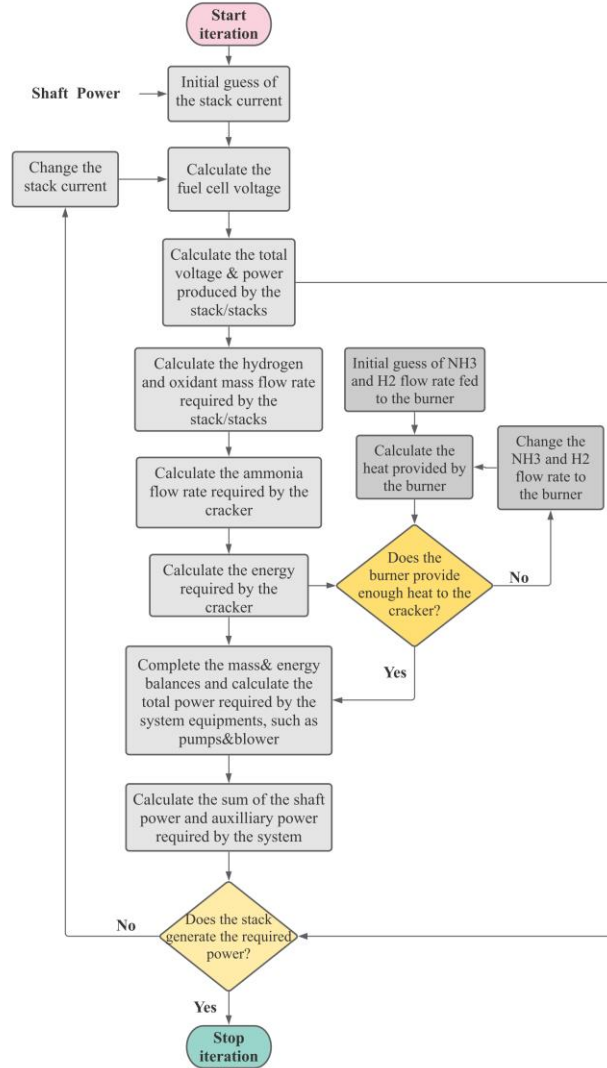


Figure 3-Model block of (a) H2 PEMFC systems (b) NH3 PEMFC system (2 column)

4.2 Performance Analysis

According to the mass flow rates, enthalpies, pressure and temperature obtained from the thermodynamic model, the performance of the systems respect to the following performance indicators: system energy efficiency, fuel consumption, volume and mass of the system, cost, environmental impacts, can be analysed.

4.2.1 Energy and exergy efficiency

The system energy efficiency is defined as

$$\eta_{en,system} = \frac{PWR_{propulsion\ shaft} + PWR_{hotel} + PWR_{manoeuvring}}{\dot{m}_{fuel} \cdot LHV_{fuel}} \quad (7)$$

where LHV_{fuel} is the low heating value of the fuel and $\dot{m}_{fuel}$ is the required mass flow rate of the fuel flowing into the system.

The system exergy efficiency is defined as

$$\eta_{ex,system} = \frac{PWR_{propulsion\ shaft} + PWR_{hotel} + PWR_{manoeuvring}}{\dot{m}_{fuel} \cdot ex_{fuel,in}} \quad (8)$$

where $ex_{fuel,in}$ is the specific exergy of the fuel into the system.

4.2.2 System fuel consumption and tank volume calculation

The system fuel consumption for the target ships to complete the journey is given by,

$$m_{fuel\ consumption} = \sum_i \dot{m}_{fuel,i} \cdot t_i \quad (9)$$

where i represents the load factor shown in load profile table (Table 4); $\dot{m}_{fuel,i}$ is the mass flow rate of the fuel required for the load factor i ; t_i is the time spent by the ships on each load factor i . After obtaining the amount of fuel required, the volume and mass of the fuel tank can be calculated using the method presented in Ref.[65]. The detail of the tank calculation is also provided in supplementary material C (see Table 6 for summary of tank properties).

Table 6-Properties of the tanks applied in the GH₂ system, LH₂ system and LNH₃ system [66]–[68]

	Temperature (K)	Pressure (10 ⁵ pa)	Tank-wall material
GH ₂ system	288.15	350	T700S carbon fibre
LH ₂ system	20.28	1.013	Al alloy 2219
LNH ₃ system	298.15	10.05	stainless steel 316

4.2.3 Environmental impacts

The lifecycle greenhouse gas (GHG) emissions (well to propeller emissions) of the power systems are calculated from the GHG emission factor ($EF_{lifecycle,GHG}$) of the fuels (g CO₂eq emitted /kg fuel consumed),

$$LCE_{GHG} = m_{fuel\ consumption} \cdot EF_{lifecycle,GHG} \quad (10)$$

The ammonia system and hydrogen system can reach zero GHG emission during operation, however, they might emit significant GHGs during production, distribution, and storage stages. The emissions can be lowest if the hydrogen and ammonia are green hydrogen produced from electrolysis using renewable energy and green ammonia produced from that green hydrogen, which is assumed in this study (see Table 7).

Table 7-Lifecycle GHG emissions of different fuels [6], [69]–[72]

	Lifecycle GHG Emission Factor ($EF_{lifecycle,GHG}$) *	
	kg CO ₂ eq /kg fuel	
ULSFO (for cargo ship ICE system)	3.613	
MGO/LSMGO (for water taxi ICE system)	2.677	
Green hydrogen	0.967	
Green ammonia	0.605	

*100-year time frame global warming potential is used to convert the CH₄ and N₂O emissions to CO₂ equivalent.

Except for the lifecycle GHG emissions, the operational emissions (OE) of the NO_x, SO_x, PM and NH₃ are used as another indicator for the systems environmental impacts. The operational emissions from the designed hydrogen and ammonia systems can be obtained from the thermodynamic models. For comparison, the operational emissions from the conventional marine engine and ammonia-fuel oil dual fuel engine are determined from the operational emission factors (g emission/kWh delivered to the shaft):

$$OE_k = EF_{\text{main engine},k} \sum_{ME,i} L_{f,i} RP_i t_i + EF_{\text{Auxiliary engine},k} \sum_{AE,i} L_{f,i} RP_i t_i \quad (11)$$

where EF_k (g/kWh) is the average operational emission factor of the pollutant k over different load levels, $L_{f,i}$ is the load factor i , RP_i is the rated power of the engine. The operational emission factors for different systems are shown in Table 8.

Table 8- Operational Emission factors of the marine diesel engine and ammonia-fuel oil dual fuel engine [16]–[18], [34], [72]–[74]

	EF _{NOx} g/kWh	EF _{Sox} g/kWh	EF _{PM} g/kWh	EF _{NH3} g/kWh
LSMGO diesel engine for water taxi	6	0.3	0.3	0
ULSFO diesel engine for cargo ship	ME:14 AE:9	ME:0.3 AE:0.4	ME:0.4 AE:0.4	0
NH ₃ -LSMGO dual fuel engine for water taxi	2.4-15	0.03	0.04	20
NH ₃ -ULSFO dual fuel engine for cargo ship	ME&AE: 14.4	ME&AE: 0.03	ME&AE: 0.04	ME&AE: 20

Note: ME is main engine; AE is auxiliary engine; LSMGO is low-sulfur marine gasoil (0.1 mass% S) ; ULSFO is ultra-low sulfur fuel oil (0.1 mass% S); All the emission factors are for the marine propulsion systems without aftertreatment, such as SCR and ammonia sorption column.

4.2.4 Cost

The total cost of the designed systems can be divided into Capital Expenditures (CAPEX), which is mainly the purchasing cost of equipment in this study, and Operating Expenses (OPEX), which consist of the operating and maintenance cost (O&M cost) of the equipment and the fuel cost.

With a view to compare the costs of different systems, cumulative costs are calculated over a lifetime of 25 years:

$$Cost_{cum} = CAPEX + \sum_{n=1}^{25} \frac{OPEX}{(1+r)^n} \quad (12)$$

where r is the discount rate, which is assumed to be 5% and n is the age of the ship.

The predicted fuel prices over the ship lifetime are shown in Table 9. Driven by expected reductions of electrolyser prices and renewable energy costs, the price of green hydrogen and green ammonia are expected to fall in the future. The fuel oil prices are volatile and difficult to predict. In this study, the fuel oil prices are predicted based on the crude oil prices projection published by US Energy Information Administration (EIA) [75]. Assuming steady economic growth, increasing oil demand and decreasing oil production rate, the oil prices will rise in the future [75].

Table 9- Predicted fuel prices over the ship lifetime

Year	Predicted Price (£/10 ³ kg)					
	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	
ULSFO	380	536	648	715	760	[75], [76]
LSMGO	420	593	716	791	840	[75], [76]
Green gaseous hydrogen	4104	3040	1976	1710	1444	[77]–[79]
Green liquid hydrogen	4712	3648	2584	2280	1976	[77]–[80]
Green ammonia	771	584	396	350	304	[77]–[79], [81]

Note: The fuel costs include the fuel production cost and preparation cost (i.e. Liquefaction and compression cost) and are based on the average renewable conditions. The green ammonia cost is estimated based on the green hydrogen cost.

5. Results and discussion

This section analyses the results from the model for the water taxi and the cargo ship. According to the results, assessing and comparing the H₂ PEMFC systems and NH₃ PEMFC system for each case study with respect to different performance indicators. The performance of the conventional marine engine and ammonia-fuel oil dual fuel engine from literature are used as base cases to compare with the designed hydrogen and ammonia PEMFC systems.

5.1 Results from the thermodynamic model

Based on the modelling, a single Hydrogenics HD-30 fuel cell stack (31kW rated power) is sufficient to power the water taxi at each load factor. Conversely, 141 and 142 Hydrogenics HD-180 fuel cell stacks (198kW rated power) are required to power the cargo ship H₂ PEMFC systems and LNH₃ PEMFC system, respectively. For the cargo ship, the power generated by all the stacks is assumed to be equal. But in reality, each stack can generate different amounts of power to reach the highest overall system efficiency. The idle power (i.e. minimum operating power) of the heavy-duty PEMFC stack is about 5% of the rated power [82]. Hence, when the cargo ship is at the idle stage or at berth, only 30-50 stacks are at work for the H₂ PEMFC systems and 12-18 stacks are at work for the LNH₃ PEMFC system to reach the minimum power requirement of the stacks and at the same time, maximize the system efficiency (explained more in section 5.2.1). To provide the start-up power for the equipment, a battery of 1000 kWh, 1100 kWh and 2000 kWh are required for the cargo ship GH₂, LH₂ and LNH₃ PEMFC system while a battery of 1 kWh and 3 kWh are required for the water taxi GH₂ and LNH₃ PEMFC system. The fuel mass flow rate and power generated at different propulsion load factors for the designed water taxi systems and cargo ship systems are presented in supplementary information D.

5.2 Performance analysis

5.2.1 Energy efficiency, exergy efficiency and exergy destruction rate distribution

Figure 4 compares the system LHV energy efficiencies of different water taxi and cargo ship systems. The efficiency of the diesel engine system and the ammonia-diesel dual fuel engine system are estimated according to the studies [16], [29]–[34]. As shown in Figure 4, the H₂ and NH₃ PEMFC systems' efficiency for both case studies increases from full load to a lower load factor, owing to the lower overpotential of the fuel cell stack at lower current density, which results in higher stack efficiency. At propulsion load factors higher than 8%-10% for the H₂ (GH₂ or LH₂) PEMFC systems or higher than 36%-43% for the LNH₃ PEMFC systems, the stack efficiency dominates the system efficiency, but as the propulsion load factor reduces below this value, the power loss related to the balance of plant contributes increasingly significantly. Although most of the components (e.g. pumps) can adjust their power demand based on the output from the fuel cell, some components, such as controllers, require constant power supplied by the fuel cell stack regardless of the stack's output.

This constant power percentage will increase as the load factor reduces, which results in decreasing system efficiency. As shown in Figure 4, the optimum propulsion load factor for the H_2 PEMFC systems is about 8-10%, while that for the LNH_3 PEMFC system is about 36-43% due to the higher proportion of the balance of plant's power loss. For the cargo ship PEMFC systems operated at propulsion load factors lower than the optimum load factor, it would be beneficial if only some of the stacks are on-line to reduce the balance of plant power loss, which could maximize the system's efficiency.

For the water taxi, the GH_2 PEMFC system is the most efficient among the four systems at all propulsion load factors owing to the high thermal LHV efficiency of the stack. The LNH_3 system is also powered by the stack but around 14% (by volume) of the ammonia fuel and around 7% (by volume) of the hydrogen produced are used in the burner to provide sufficient heat to the cracker, which leads to lower system efficiency compared with the H_2 PEMFC system. The water taxi LNH_3 PEMFC system has higher LHV efficiency than the water taxi diesel engine system and the ammonia-fuel oil dual fuel engine system at all load factors. Owing to the low revolution rate, high air to fuel ratio and long stroke, the two-stroke engine for the cargo ship can operate at higher LHV efficiency than the four-stroke engine for the water taxi [83]. Therefore, for the cargo ship, the GH_2 PEMFC system has the highest LHV efficiency only if the propulsion load factor is below 48%, otherwise the ULSFO diesel engine system is the most efficient. Among the five cargo ship systems, the LNH_3 PEMFC system is the least efficient because of the extra power required by the ammonia cracker. The detail of power loss distribution of the designed system is provided in supplementary material E.

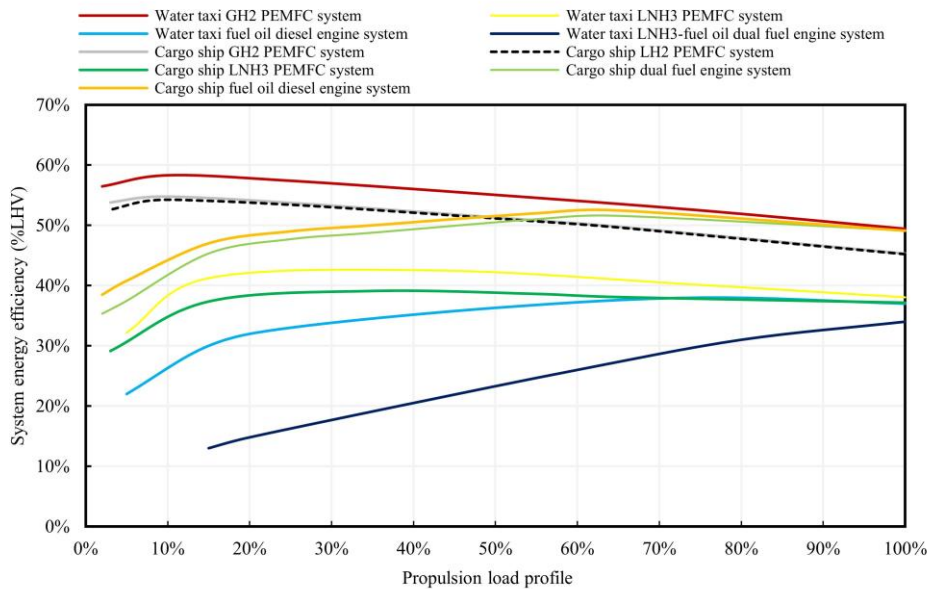


Figure 4- The system energy efficiency (%LHV) of the water taxi and cargo ship at different propulsion load factors. Note: No ammonia-diesel engine efficiency for two-stroke marine ship is stated, the ammonia-fuel oil dual fuel engine efficiency is estimated based on the Man LGIP (liquefied petroleum gas) marine dual fuel engine. Based on the document by Man, the ammonia dual fuel engine is a modified version of LGIP dual fuel engine and the engine efficiency can reach above 50% [32], [33].

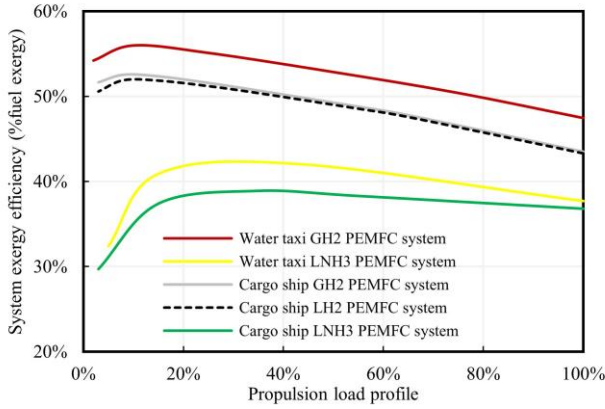


Figure 5- The system exergy efficiency (% fuel exergy) of the water taxi and cargo ship at different propulsion load factors. (1 column)

Beside the energy analysis, an exergy analysis is conducted for the designed PEMFC systems as a supplement to measure how close the systems are to ideality and to determine the sources of irreversibility, which could help to enhance the system energy utilization. Figure 5 compares the system exergy efficiencies of the designed water taxi and cargo ship PEMFC systems at different load factors. The exergy efficiencies follow similar trend as the energy efficiencies. Due to the irreversibility incurred by the extra ammonia cracker (with burner), the ammonia PEMFC systems have lower exergy efficiencies than the hydrogen PEMFC systems. Moreover, the exergy efficiencies of the cargo ship PEMFC systems are lower than that of the water taxi PEMFC systems owing to the higher destruction rate from the electrical circuitry.

The exergy efficiencies and the system energy utilization could be improved by reducing exergy destruction rates ($\dot{E}_{x,d}$). The overall exergy destruction rates of the water taxi GH_2 PEMFC systems, LNH_3 PEMFC system and the cargo ship GH_2 system, LH_2 system and LNH_3 system at full load are 26 kW, 36 kW and 26600 kW, 26800 kW and 35900 kW, respectively and their distributions are shown in Figure 6. The PEMFC contributes most significantly to the exergy destruction rate of all the designed PEMFC systems. Therefore, reducing the fuel cell destruction rate could lead to significantly improvement in the system exergy efficiencies, which might be achieved by increasing the PEMFC operating temperature and pressure, reducing membrane thickness etc. Improving the efficiency of the electric devices, such as inverters, will also improve the system exergy efficiency. For the GH_2 PEMFC system, the pressure reduction valve contributes significantly to the irreversibility because of the large pressure drop and replacing the valves with expanders might recover the pressure energy and improve the energy utilization. For the LH_2 and LNH_3 systems, the liquid fuel evaporators and heaters are significant exergy destroyers, and their destruction rate could be lowered by reducing the temperature difference. Moreover, in the LNH_3 PEMFC systems, the ammonia cracker and burner occupy 16%-17% of the exergy destruction rate. The high burner destruction rate is associated with the high entropy generation, which could be reduced by improving burner design and operation conditions (e.g., equivalence ratio). While the destruction rate of the ammonia cracker could be reduced by lowering the operating temperature of the cracker through improving cracker design or cracking catalyst. Overall, there is room to further improve the efficiency and energy utilization of the designed PEMFC systems.

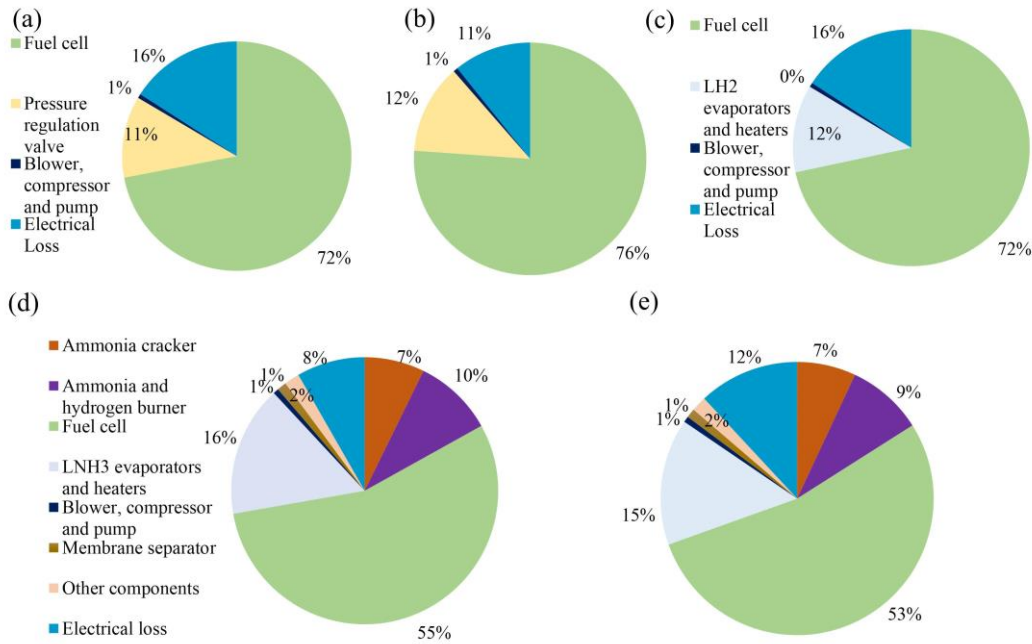


Figure 6- The exergy destruction rate distribution under full propulsion load condition for the (a) water taxi GH₂ systems (b) cargo ship GH₂ systems (c) cargo ship LH₂ system (d) water taxi LNH₃ system (e) cargo ship LNH₃ system. Note: (a) and (b) share the same legend, (d) and (e) share the same legend; other components include ammonia sorption column, SCR and valve; electrical circuit includes the controller, sensor, converter, inverter, transformer, drive, gearbox, motor.

5.2.2 System volume and mass analysis

Figure 7 (a) compares the volume and mass of different water taxi power systems, including the mass and volume of the fuel tanks with fuel to support the water taxi for 8-hour operation, all the equipment in Figure 1 (e.g. pumps, cracker and fuel cell stacks) and the batteries, converters, drive and motor in Figure 2. The diesel engine systems' volume and mass are estimated from the study [16], [29]–[34], [47]. In term of the mass and volume of the fuel tanks, the gaseous hydrogen tank has the highest volume and mass among the four systems due to the low volumetric energy density of the gaseous hydrogen and the heavy and bulky tanks required to withstand the high gaseous pressure. The fuel tank for the LNH₃ PEMFC system has smaller mass and volume than the GH₂ system but is 2.5 times larger in mass and 3.2 times larger in volume compared with the LSMGO diesel engine system. According to the studies by several researchers and companies, such as Enviu and Alewijnse Marine Systems [11], the GH₂ PEMFC system can meet the space and mass constraints of the small-scale vessels, such as the water taxi. In this study, Figure 7 (a) indicates that the LNH₃ PEMFC system has comparable mass and 42% lower system volume with respect to the hydrogen system. It is noted that the ammonia cracker with burner and purifier contribute only slightly to the water taxi LNH₃ PEMFC system's mass and volume (3.6 % and 3.0%, respectively). The water taxi LNH₃ PEMFC system is smaller and lighter than the ammonia-fuel oil dual fuel engine system because of the high efficiency and power density of the PEMFC but it is still 46% heavier and 5% bulkier than the LSMGO diesel engine system.

Figure 7 (b) compares the volume and mass of different 2600TEU cargo ship power systems, including the mass and volume of the fuel tanks with fuel to support the cargo ship traveling across

the Pacific Ocean with a nonstop voyage leg of 6,600nm and system equipment (all the equipment in Figure 1 and the batteries, converters, drive and motor in Figure 2). The volume and mass of the cargo ship diesel engine systems are estimated from the Ref. [6], [84], [85]. According to the study by Mao et al. [50], the available space of fuel storage (i.e. maximum fuel tank volume) of the 2000 – 2999 TEU cargo ship is 3330 to 4700 m³. Therefore, as seen in the Figure 7 (b), the GH₂ PEMFC system (350bar), which requires fuel tank with volume of 9100 m³ is too bulky for the long-distance and large-scale shipping application. Even if increasing the pressure of the tank to 700bar, the volume of gaseous hydrogen tank, which is around 6695 m³, is still not within the volume limit. Conversely, the LH₂ PEMFC system, LNH₃ PEMFC system and ammonia dual fuel engine system can all meet the constraint. The LNH₃ PEMFC system is less beneficial than the LH₂ PEMFC system in term of the mass due to the lower fuel mass energy density and the additional ammonia cracker required. However, the LNH₃ is easier to handle, and has a more mature supply chain compared with the LH₂, which enhances its potential to be applied as the ship fuel at large scale.

The detailed mass, volume and cost of the GH₂, LH₂ and LNH₃ systems' components is provided in supplementary material F.

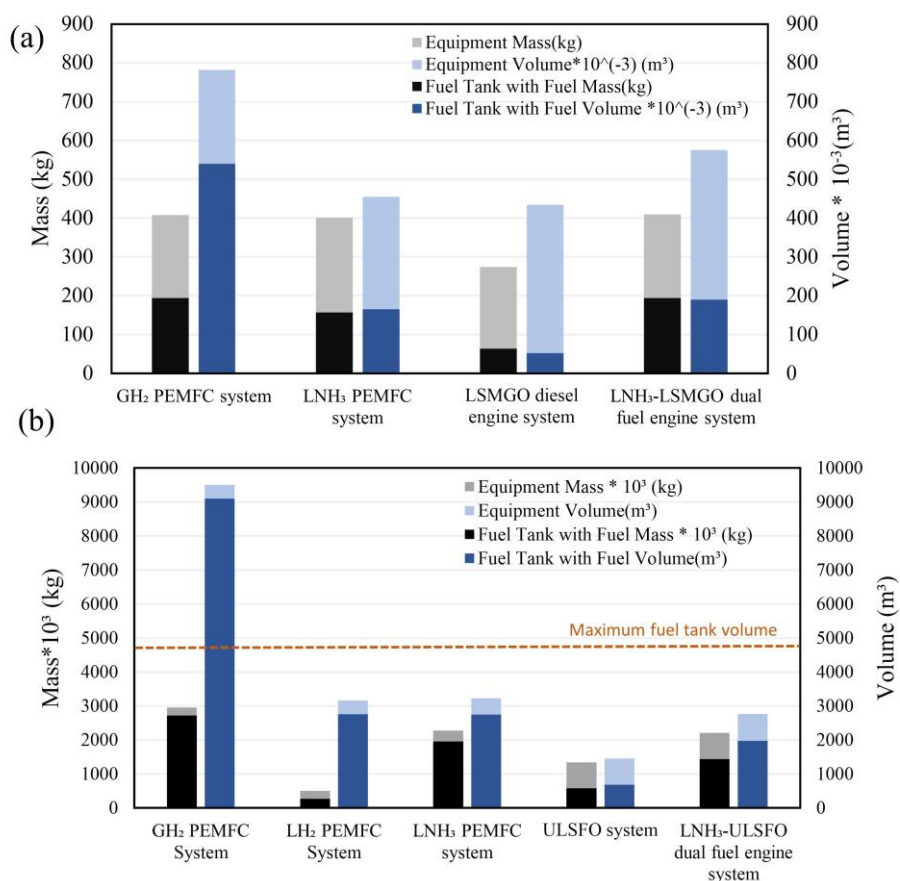


Figure 7-Overall system volume and mass analysis of the (a) 12-passenger water taxi (b) 2600TEU cargo ship

5.2.3 Environmental impacts

The lifecycle GHG emissions of the water taxi and cargo ship based on different power systems are shown in Figure 8. The hydrogen and ammonia are assumed to be green hydrogen and green ammonia produced from electrolysis using renewable energies. In contrast with the fuel oil diesel engine system, the H_2 PEMFC system, LNH_3 PEMFC system and ammonia-fuel oil dual fuel engine system can reduce the life cycle GHG emissions by 91%, 88% and 72%, respectively for the water taxi and by 91%, 88% and 80%, respectively for the cargo ship.

Instead of just the lifecycle GHG emissions, the operational emissions of different marine systems are also analysed. The GH_2 and LH_2 PEMFC system can reach zero emissions during operation while the LNH_3 system can also prevent the PM and SO_x emissions but will emit some NO_x (2103 kg NO_x /year for cargo ship and 1.6 kg NO_x /year for water taxi) due to the combustion of hydrogen and ammonia in the burner. Nevertheless, the LNH_3 system (with SCR) can reach operational NO_x reduction of 95% and 98% compared with the fuel oil diesel engine systems with SCR for the water taxi and cargo ship, respectively. Switching the fuel oil diesel engine to an ammonia-fuel oil dual fuel engine could curtail the operational PM emissions by 87%-90% and operational SO_x emissions by 90%. However, the ammonia-fuel oil dual fuel engine suffers from significant ammonia slip and NO_x emissions. The detail of the operational emissions of different water taxi and cargo ship power systems is provided in supplementary material G.

For the cargo ship, the PEMFC system offers another advantage over the diesel engine system because it could replace the diesel genset for the auxiliary power generation. The replacement of the HFO gensets by fuel cells for auxiliary power can reduce the operational SO_x , NO_x and PM emissions by around 7400 kg/year, 5500 kg/year and 900 kg /year, respectively. Although the genset emissions are small compared with the main engine emissions, they lead to significant health impacts on coastal residents. The gensets are used to provide the auxiliary power for the ships when they are berthing or in the harbour, therefore, can cause direct emissions to the closed coastal area.

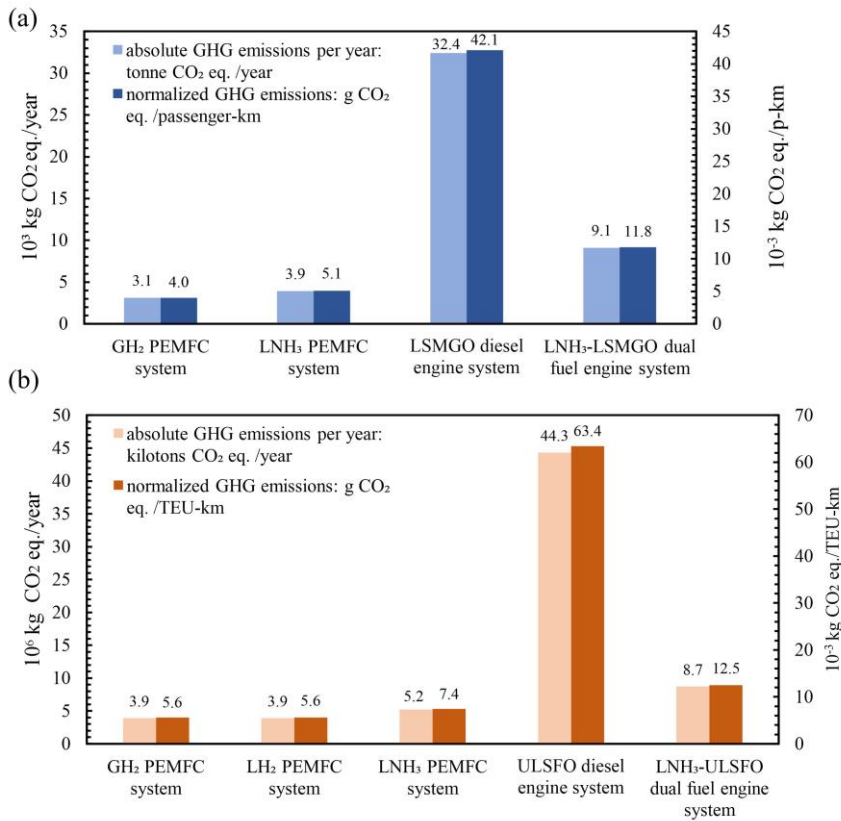


Figure 8- Lifecycle GHG emissions of different (a) 12-passenger water taxi power systems (b) 2600TEU cargo ship power systems

5.2.4 Cost

The cumulative cost of different water taxi power systems and cargo ship power systems with a lifetime of 25 years are compared in Figure 9. The system cost includes the cost of the fuel over the system lifetime (Table 9) and the cost of the system equipment (all the equipment in Figure 1 and the batteries, converters, drive and motor in Figure 2). For the water taxi case study, the GH₂ PEMFC system is more cost-efficient than the LNH₃ PEMFC system owing to the lower fuel consumption and lower CAPEX. The water taxi LNH₃ PEMFC system has similar cost to the ammonia dual fuel engine but is 44% and 105% more costly than the GH₂ PEMFC system and LSMGO diesel engine. For the cargo ship case study, the GH₂ PEMFC system, LH₂ PEMFC system and LNH₃ PEMFC system have comparable costs, which are around 108%, 112% and 116% higher than the ULSFO diesel engine system, respectively. Owing to the high cost of the large gaseous hydrogen tank required for the cross-ocean voyage, the cost difference between the LNH₃ PEMFC system and GH₂ PEMFC system for the cargo ship is smaller than that for the water taxi.

The above cumulative cost analysis is based on the case with no carbon tax or similar policy measure. Based on the lifecycle GHG emissions in section 5.2.3, a carbon tax of 75 £/tonne CO₂-eq and 191 £/tonne CO₂-eq, respectively, would make the costs of the water taxi GH₂ and LNH₃ PEMFC systems competitive to the conventional fuel oil heat engine system. While the carbon tax needed for the cargo ship GH₂, LH₂ and LNH₃ PEMFC systems are 145, 149, 159 £/tonne CO₂-eq, respectively. The carbon taxes needed are 50%-280% higher than the current carbon price level in UK (50£/tonne CO₂-eq)

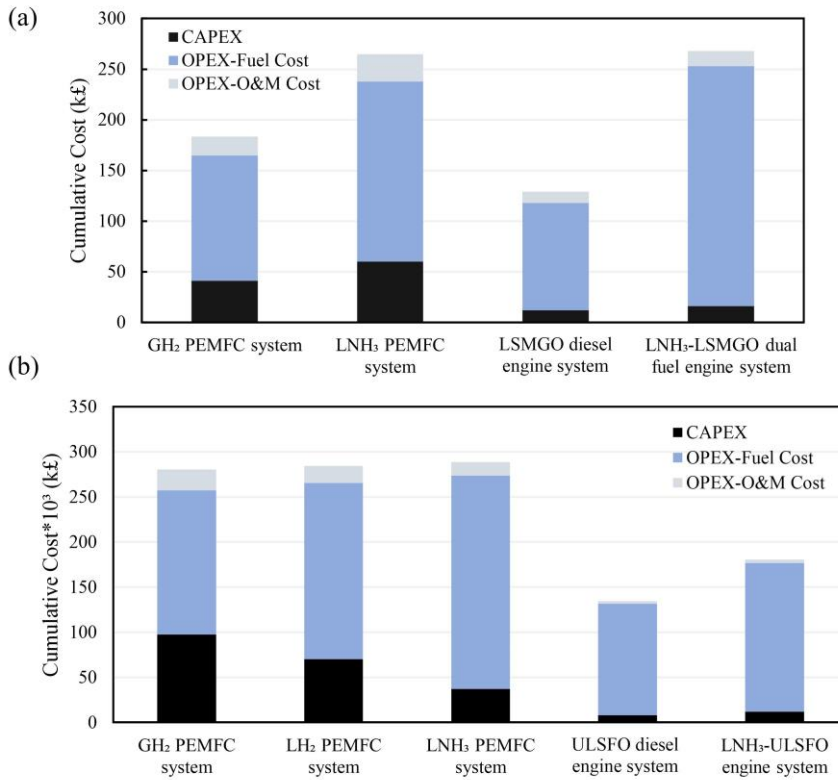


Figure 9-Cumulative cost analysis of different (a) 12-passenger water taxi power systems and (b) 2600TEU cargo ship power systems over a lifetime of 25 years (1.5 column)

6. Conclusions

In this paper, pure gaseous hydrogen, and liquid hydrogen PEMFC propulsion systems and an integrated ammonia cracker with PEMFC propulsion system are designed. A model is developed for the designed systems and applied to two case studies, a 25kW water taxi and a 2600TEU container ship, to access their performances in term of the fuel consumption, efficiency and exergy destruction rate, mass and volume occupation, environmental impacts and the costs. The performance of the conventional marine engine and ammonia-fuel oil dual fuel engine from literature are used as base-cases for comparison.

In this regard, the main findings of the study are listed below:

- The LHV energy efficiency of the GH₂ PEMFC system is 45.2% - 58.3 %, which is around 22%-85% more energy-efficient than the LNH₃ PEMFC system depending on the ship scale and the load factor. Compared with the conventional fuel-oil engine, the LNH₃ PEMFC system has higher LHV efficiency for the water taxi but has lower efficiency for the cargo ship.

- The PEMFCs contribute most significantly to the exergy destruction rate for all the designed PEMFC systems. Hence, improving the stack exergy efficiency would lead to a significant improvement in the system energy utilization.
- The GH_2 PEMFC system, which requires a fuel tank with volume of 9100 m^3 cannot meet the space constraint of 4700 m^3 for the 2600TEU cargo ship while the LH_2 PEMFC system and the LNH_3 PEMFC system, whose fuel tank volume is 2754 m^3 and 2748 m^3 , respectively, are within the volume limits. Therefore, in term of mass and volume, the GH_2 PEMFC system might not be suitable for the large-scale and long-distance shipping marine application.
- The designed GH_2 , LH_2 , LNH_3 PEMFC systems using green hydrogen and ammonia can reach nearly zero operational emissions. Compared to the conventional fuel oil engine system, the GH_2 system, LH_2 system and LNH_3 system could reduce lifecycle GHG emissions by around 91%, 91% and 88%, which all meet the IMO target of 50% GHG reduction by 2050.
- Taking into account the predicted fuel prices over the ship system life of 25-year, the cargo ship GH_2 , LH_2 and LNH_3 system have cumulative costs of 280M£, 284M£ and 289M£, respectively, while the water taxi GH_2 system and LNH_3 system have cumulative costs of 184k£ and 265k£, respectively. Further carbon policy measures and cost reduction in green fuels and fuel cells are required to bring the designed PEMFC systems down by 31%-54% to make them cost competitive to the fuel oil engine system.

Nomenclature

Symbols

GH_2	Gaseous Hydrogen
LH_2	Liquid Hydrogen
LNH_3	Liquid Ammonia
C_p	Specific heat (J/kg·K)
n	Number of electrons
I	Current (A)
i	Current density (A/m ²)
F	Faraday Constant (s·A/mol)
E	Potential (V)
V	Potential loss (V)
R	Resistance (Ω)
γ	Water content
N	Number
PWR	Power (W)
$\dot{m}$	Mass flow rate (mol/s)
$\dot{n}$	Molar flow rate (mol/s)
P	Pressure (Pa), pump
$\dot{Q}$	Heat transfer rate (W)
$\dot{W}$	Work done (W)
$\Delta \dot{H}$	Enthalpy change rate (W)
$\widehat{H}_1$	Specific enthalpy (J/mol)
$\widehat{S}_1$	Specific entropy (J/mol K)
ex	Specific exergy (J/mol)
$\Delta \dot{E}_{KE}$	Kinetic energy change rate (W)
$\Delta \dot{E}_{PE}$	Potential energy change rate (W)

$\dot{E}_{Xd}$

Exergy destruction rate (W)

R

Gas constant (J/mol K)

T

Temperature (K)

k

Heat capacity ratio

w

Specific work done (J/g) or (J/mol)

v

Specific volume (m⁻³)

h

Heat transfer coefficient (W/m² K)

RP

Rated power (W)

L_f

Load factor

Greek letters

η

Efficiency

ζ

Stoichiometric coefficient

σ

Stefan-Boltzmann constant

ε

Emissivity

Acronyms

ECAs

Emissions Control Areas

PM

Particulate Matters

HFO

Heavy Fuel Oil

ULSFO

Ultra-low Sulfur Fuel Oil

MGO

Marine Gasoil

PEMFC

Proton exchange membrane fuel cell

SCR

Selective Catalytic Reduction

SOFC

Solid oxide fuel cell

EF

Emission factor

GHG

Greenhouse gas

CAPEX

Capital expenditure

OPEX

Operating expenditure

O&M

Operating and maintenance

Subscripts

FC

Fuel cell

oc

open circuit

0

Reference temperature

amb

ambient

act

activation

conc

concentration

ohm

Ohmic

m

membrane

i

species or component

f

formation

in

inlet

out

outlet

Superscripts

0

Standard state value

References

- [1]M. Sofiev *et al.*, “Cleaner fuels for ships provide public health benefits with climate tradeoffs,” *Nature Communications*, vol. 9, no. 1, Art. no. 1, Feb. 2018, doi: 10.1038/s41467-017-02774-9.
- [2]BRS Group, “Shipbuilding Annual Review.” 2019. [Online]. Available: https://www.brsbrokers.com/assets/review_splits/BRS-Review2019-01-Shipbuilding.pdf
- [3]International Maritime Organization, “Greenhouse Gas Studies 2014,” 2014. <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Greenhouse-Gas-Studies-2014.aspx> (accessed Apr. 18, 2020).
- [4]International Maritime Organization, “Sulphur 2020 – cutting sulphur oxide emissions,” 2020. <http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx> (accessed Apr. 18, 2020).
- [5]International Maritime Organization, “Nitrogen oxides (NO_x) – Regulation 13,” 2011. [http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-\(NO_x\)-%E2%80%93Regulation-13.aspx](http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93Regulation-13.aspx) (accessed Apr. 18, 2020).
- [6]K. Kim, G. Roh, W. Kim, and K. Chun, “A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments,” *Journal of Marine Science and Engineering*, vol. 8, no. 3, Art. no. 3, Mar. 2020, doi: 10.3390/jmse8030183.
- [7]Dr.-Ing. Yves Wild, “Determination of energy cost of electrical energy on board sea-going vessels.” 2005. [Online]. Available: http://www.effship.com/PartnerArea/MiscPresentations/Dr_Wild_Report.pdf
- [8]Shell, “Ultra-Low Sulphur Fuel Oil | Shell Global.” <https://www.shell.com/business-customers/marine/fuel/ulsfo.html> (accessed Feb. 28, 2021).
- [9]P. Balcombe *et al.*, “How to decarbonise international shipping: Options for fuels, technologies and policies,” *Energy Conversion and Management*, vol. 182, pp. 72–88, Feb. 2019, doi: 10.1016/j.enconman.2018.12.080.
- [10]H. Kobayashi, A. Hayakawa, K. D. K. A. Somarathne, and E. C. Okafor, “Science and technology of ammonia combustion,” *Proceedings of the Combustion Institute*, vol. 37, no. 1, pp. 109–133, Jan. 2019, doi: 10.1016/j.proci.2018.09.029.
- [11]T. Tronstad, H. H. Åstrand, G. P. Haugom, and L. Langfeldt, “EMSA Study on the use of Fuel Cells in Shipping.” 2017. Accessed: Sep. 02, 2020. [Online]. Available: <http://www.emsa.europa.eu/emsa-homepage/2-news-a-press-centre/news/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html>
- [12]C. Raucci, J. Calleya, S. Suarez De La Fuente, and R. Pawling, “Hydrogen on board ship: a first analysis of key parameters and implications,” *SCC Conference 2015*, Nov. 24, 2015. <https://strathprints.strath.ac.uk/cgi/search/advanced> (accessed Apr. 18, 2020).
- [13]A. Valera-Medina, H. Xiao, M. Owen-Jones, W. I. F. David, and P. J. Bowen, “Ammonia for power,” *Progress in Energy and Combustion Science*, vol. 69, pp. 63–102, Nov. 2018, doi: 10.1016/j.pecs.2018.07.001.
- [14]A. T. Wijayanta and M. Aziz, “Ammonia production from algae via integrated hydrothermal gasification, chemical looping, N₂ production, and NH₃ synthesis,” *Energy*, vol. 174, pp. 331–338, May 2019, doi: 10.1016/j.energy.2019.02.190.
- [15]M. F. Ezzat and I. Dincer, “Comparative assessments of two integrated systems with/without fuel cells utilizing liquefied ammonia as a fuel for vehicular applications,” *International Journal of Hydrogen Energy*, vol. 43, no. 9, pp. 4597–4608, Mar. 2018, doi: 10.1016/j.ijhydene.2017.07.203.
- [16]A. J. Reiter and S.-C. Kong, “Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel,” *Fuel*, vol. 90, no. 1, pp. 87–97, Jan. 2011, doi: 10.1016/j.fuel.2010.07.055.

- [17]MAN Energy Solutions, “MAN B&W two-stroke engine operating on ammonia.” MAN Energy Solutions, 2020. [Online]. Available: https://www.man-es.com/docs/default-source/marine/tools/man-b-w-two-stroke-engine-operating-on-ammonia.pdf?sfvrsn=544dc811_12
- [18]T. Brown, “MAN Energy Solutions: an ammonia engine for the maritime sector,” *Ammonia Energy Association*, 2019. <https://www.ammoniaenergy.org/articles/man-energy-solutions-an-ammonia-engine-for-the-maritime-sector/> (accessed Apr. 19, 2020).
- [19]M. F. Ezzat and I. Dincer, “Development and assessment of a new hybrid vehicle with ammonia and hydrogen,” *Applied Energy*, vol. 219, pp. 226–239, Jun. 2018, doi: 10.1016/j.apenergy.2018.03.012.
- [20]Y. Zhao *et al.*, “An Efficient Direct Ammonia Fuel Cell for Affordable Carbon-Neutral Transportation,” *Joule*, vol. 3, no. 10, pp. 2472–2484, Oct. 2019, doi: 10.1016/j.joule.2019.07.005.
- [21]K. H. M. Al-Hamed and I. Dincer, “A novel ammonia solid oxide fuel cell-based powering system with on-board hydrogen production for clean locomotives,” *Energy*, vol. 220, p. 119771, Apr. 2021, doi: 10.1016/j.energy.2021.119771.
- [22]Y. Chu, Y. Wu, J. Chen, S. Zheng, and Z. Wang, “Design of energy and materials for ammonia-based extended-range electric vehicles,” *Energy Procedia*, vol. 158, pp. 3064–3069, Feb. 2019, doi: 10.1016/j.egypro.2019.01.991.
- [23]M. Ezzat and I. Dincer, “Exergoeconomic analysis and optimization of a new hybrid fuel cell vehicle,” *International Journal of Hydrogen Energy*, vol. 45, no. 9, pp. 5734–5744, Feb. 2020, doi: 10.1016/j.ijhydene.2019.07.104.
- [24]M. Wang, J. Li, L. Chen, and Y. Lu, “Miniature NH₃ cracker based on microfibrous entrapped Ni-CeO₂/Al₂O₃ catalyst monolith for portable fuel cell power supplies,” *International Journal of Hydrogen Energy*, vol. 34, no. 4, pp. 1710–1716, Feb. 2009, doi: 10.1016/j.ijhydene.2008.11.103.
- [25]C. Pochari, “Small scale highly compact microchannel ammonia crackers,” *Novel Rotorcraft Designs*, Sep. 20, 2019. <https://pocharitechnologies.com/2019/09/20/micro-ammonia-cracker-for-on-demand-mobile-hydrogen/> (accessed Apr. 19, 2020).
- [26]H. M. A. Hunter *et al.*, “Demonstrating hydrogen production from ammonia using lithium imide – Powering a small proton exchange membrane fuel cell,” *Journal of Power Sources*, vol. 329, pp. 138–147, Oct. 2016, doi: 10.1016/j.jpowsour.2016.08.004.
- [27]D. Viano, “Pilot-scale Ammonia-to-Hydrogen refuelling system for Fuel Cell electric vehicles,” 2019. [Online]. Available: <https://energy.anu.edu.au/files/David%20Viano.pdf>
- [28]B. A. van Hassel *et al.*, “Ammonia sorbent development for on-board H₂ purification,” *Separation and Purification Technology*, vol. 142, pp. 215–226, Mar. 2015, doi: 10.1016/j.seppur.2014.12.009.
- [29]J. Lasocki, M. Bednarski, and M. Sikora, “Simulation of ammonia combustion in dual-fuel compression-ignition engine,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 214, no. 1, p. 012081, Jan. 2019, doi: 10.1088/1755-1315/214/1/012081.
- [30]E. Eastlack, “Zero Emission Super-Yacht,” presented at the 2019 Fourteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), 2019. [Online]. Available: <https://aqualisbraemar.com/wordpress/wp-content/uploads/2019/09/Zero-Emission-Super-Yacht-in-EVER2019.pdf>
- [31]A. Stiel and M. Skyllas-Kazacos, “Feasibility Study of Energy Storage Systems in Wind/Diesel Applications Using the HOMER Model,” *Applied Sciences*, vol. 2, no. 4, Art. no. 4, Dec. 2012, doi: 10.3390/app2040726.
- [32]MAN Energy Solutions, “MAN B&W ME-LGIP dual-fuel engines.” MAN Energy Solutions, 2018. [Online]. Available: <https://www.man-es.com/docs/default-source/marine/144363-man->

lgip_factsheet_-7.pdf?sfvrsn=3b8ccb4c_12

[33]MAN Energy Solutions, “Propulsion of 2,200 - 3,000 teu container vessels.” MAN Energy Solutions, 2019. [Online]. Available: <https://www.man-es.com/marine/products/planning-tools-and-downloads/technical-papers/2>

[34]A. J. Reiter and S.-C. Kong, “Demonstration of Compression-Ignition Engine Combustion Using Ammonia in Reducing Greenhouse Gas Emissions,” *Energy Fuels*, vol. 22, no. 5, pp. 2963–2971, Sep. 2008, doi: 10.1021/ef800140f.

[35]G. Petitpas, “Boil-off losses along LH2 pathway,” Lawrence Livermore National Lab. (LLNL), Livermore, CA (United States), LLNL-TR-750685, Apr. 2018. doi: 10.2172/1466121.

[36]M. Li *et al.*, “Review on the research of hydrogen storage system fast refueling in fuel cell vehicle,” *International Journal of Hydrogen Energy*, vol. 44, no. 21, pp. 10677–10693, Apr. 2019, doi: 10.1016/j.ijhydene.2019.02.208.

[37]Morgan, “Morgan Produce Data Book.” 2019. [Online]. Available: https://www.morganthermalceramics.com/media/7699/morgan-advanced-materials_thermal-ceramics-product-data-book-e-version_2.pdf

[38]C. Pochari, “Compact PEMFC grade NH3 based hydrogen generation system,” *Novel Rotorcraft Designs*, Sep. 26, 2019. <https://pocharitechnologies.com/2019/09/26/compact-pem-grade-nh3-based-hydrogen-generation-system/> (accessed Sep. 02, 2020).

[39]N. Vanderborgh and J. M. Ohi, “Hydrogen Fuel Quality Specifications for Polymer Electrolyte Fuel Cells in Road Vehicles,” U.S. Department of Energy, U.S., 2016. [Online]. Available: https://www.energy.gov/sites/prod/files/2016/11/f34/fcto_h2_fuel_quality_specs_pem_fc_road_vehicles.pdf

[40]M. Dolan, D. Viano, M. Langley, and K. Lamb, “Tubular vanadium membranes for hydrogen purification,” Mar. 2018, doi: <https://doi.org/10.1016/j.memsci.2017.12.031>.

[41]H.-S. Kim *et al.*, “Current Catalyst Technology of Selective Catalytic Reduction (SCR) for NOx Removal in South Korea,” *Catalysts*, vol. 10, no. 1, Art. no. 1, Jan. 2020, doi: 10.3390/catal10010052.

[42]O. Kröcher, M. Elsener, M.-R. Bothien, and W. Dölling, “Pre-Turbo Scr - Influence of Pressure on NOx Reduction,” *MTZ Worldw*, vol. 75, no. 4, pp. 46–51, Apr. 2014, doi: 10.1007/s38313-014-0140-x.

[43]N. A. Hussein, A. Valera-Medina, and A. S. Alsaegh, “Ammonia- hydrogen combustion in a swirl burner with reduction of NOx emissions,” *Energy Procedia*, vol. 158, pp. 2305–2310, Feb. 2019, doi: 10.1016/j.egypro.2019.01.265.

[44]T. Meyer, “Ammonia Combustion with Near-Zero Pollutant Emissions.” 2018. [Online]. Available: http://rsof.org/images/NO_CO2_FLAME_CONSTRUCTION_NH3.pdf

[45]S. Hopkins, “High-Performance Palladium Based Membrane for Hydrogen Separation and Purification,” Pall Corporation, Jan. 2012. doi: 10.2172/1057924.

[46]Hydrogenics Corporation, “HYPM-HD 30 POWER MODULE.” Hydrogenics Corporation, 2016. [Online]. Available: <http://www.hydrogenics.com/wp-content/uploads/HyPM-30-Spec-Sheet.pdf>

[47]L. Henderik, “Solid Oxide Fuel Cell Propulsion System Fueled by Ammonia: Subjected to a vessel from the Watertaxi Rotterdam Company,” 2020, Accessed: Sep. 02, 2020. [Online]. Available: <https://repository.tudelft.nl/islandora/object/uuid%3A42e5cf5d-454e-4e4f-a041-8419f9145597>

[48]FleetMon, “MSTX 12 (High speed craft),” *FleetMon.com*, 2020.

https://www.fleetmon.com/vessels/mstx-12_0_16698376/?language=en (accessed Sep. 02, 2020).

- [49]A. Aijjou, L. Bahatti, and A. Raihani, "Study on container ship energy consumption," *WIT Transactions on Ecology and the Environment*, vol. Vol 237, 2019, doi: doi:10.2495/ESUS190031.
- [50]Xiaoli Mao, "Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels? | International Council on Clean Transportation," 2020 International Council on Clean Transportation, 2020. Accessed: Sep. 02, 2020. [Online]. Available: <https://theicct.org/publications/zero-emission-container-corridor-hydrogen-2020>
- [51]Allied Market Research, "Water Taxi Market Growth, Key Drivers and Competitive Analysis - 2026," 2020. <https://www.alliedmarketresearch.com/water-taxi-market> (accessed Sep. 02, 2020).
- [52]A. A. Pesaran, G.-H. Kim, and J. D. Gonder, "PEM Fuel Cell Freeze and Rapid Startup Investigation," National Renewable Energy Laboratory, NREL/MP-540-38760, 2005. [Online]. Available: <https://www.nrel.gov/docs/gen/fy05/38760.pdf>
- [53]Grannell, Shawn and Gillespie, Donald E, "Autothermal ammonia cracker," 13/537,125 [Online]. Available: <https://patentimages.storage.googleapis.com/e5/51/7f/ba6fa4a1764b91/US20120276463A1.pdf>
- [54]N. de Vries, "Safe and effective application of ammonia as a marine fuel," Delft University of Technology, 2019. Accessed: Apr. 18, 2020. [Online]. Available: <https://repository.tudelft.nl/islandora/object/uuid%3Abe8cbe0a-28ec-4bd9-8ad0-648de04649b8>
- [55]James Castonguay, Ph.D, "International Shipping: Globalization In Crisis." [Online]. Available: https://www.visionproject.org/images/img_magazine/pdfs/international_shipping.pdf
- [56]Shagar, S. Jayasinghe, and H. Enshaie, "Effect of Load Changes on Hybrid Shipboard Power Systems and Energy Storage as a Potential Solution: A Review," 2017. doi: 10.3390/INVENTIONS2030021.
- [57]Hydrogenics, "HYPM-HD 180 POWER MODULE." 2019. [Online]. Available: <http://www.hydrogenics.com/wp-content/uploads/HyPM-180-SpecSheet.pdf>
- [58]Zhifeng Xia, "Effect of operating conditions on performance of proton exchange membrane fuel cell with anode recirculation," *Energy Procedia*, vol. 158, pp. 1829–1834, Feb. 2019, doi: 10.1016/j.egypro.2019.01.428.
- [59]A. Mokmeli and S. Asghari, "An investigation into the effect of anode purging on the fuel cell performance," *International Journal of Hydrogen Energy*, vol. 35, no. 17, pp. 9276–9282, Sep. 2010, doi: 10.1016/j.ijhydene.2010.03.079.
- [60]J. Han, J. Park, and S. Yu, "Control strategy of cooling system for the optimization of parasitic power of automotive fuel cell system," *International Journal of Hydrogen Energy*, vol. 40, no. 39, pp. 13549–13557, Oct. 2015, doi: 10.1016/j.ijhydene.2015.08.067.
- [61]P. Wu and R. Bucknalla, "Marine propulsion using battery power." 2016. [Online]. Available: <https://conferences.ncl.ac.uk/media/sites/conferencewebsites/scc2016/1.4.2.pdf>
- [62]Rolando Guidelli, "Defining the transfer coefficient in electrochemistry: An assessment (IUPAC Technical Report)1," 2014.
- [63]S. T. J. Ranta, "Electrical and mechanical integration of polymer electrolyte membrane fuel cell into electric bus test platform," p. 110, 2018.
- [64]A. Rabbani and M. Rokni, "Dynamic characteristics of an automotive fuel cell system for transitory load changes," *Sustainable Energy Technologies and Assessments*, vol. 1, pp. 34–43, Mar. 2013, doi: 10.1016/j.seta.2012.12.003.
- [65]R. Turton, R. C. Bailie, W. B. Whiting, J. A. Shaeiwitz, and D. Bhattacharyya, *Analysis, Synthesis, and Design of Chemical Processes*. Pearson Education, 2012.
- [66]British Stainless Steel Association, "Article: Selection of stainless steels for handling ammonia

- (NH₃),” 2020. <https://www.bssa.org.uk/topics.php?article=36> (accessed Sep. 02, 2020).
- [67]C. Winnefeld, T. Kadyk, B. Bensmann, U. Krewer, and R. Hanke-Rauschenbach, “Modelling and Designing Cryogenic Hydrogen Tanks for Future Aircraft Applications,” *Energies*, vol. 11, no. 1, pp. 1–23, 2018.
- [68]S. Sapre, K. Pareek, and M. Vyas, “Investigation of structural stability of type IV compressed hydrogen storage tank during refueling of fuel cell vehicle,” *Energy Storage*, vol. 2, no. 4, p. e150, 2020, doi: 10.1002/est2.150.
- [69]P. Gilbert, C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy, “Assessment of full life-cycle air emissions of alternative shipping fuels,” *Journal of Cleaner Production*, vol. 172, pp. 855–866, Jan. 2018, doi: 10.1016/j.jclepro.2017.10.165.
- [70]E4tech (UK) Ltd, “H₂ Emission Potential Literature Review,” E4tech (UK) Ltd, 2018. [Online]. Available: [ssets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/798243/H2_Emission_Potential_Report_BEIS_E4tech.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/798243/H2_Emission_Potential_Report_BEIS_E4tech.pdf)
- [71]M. Miller, A. S. K. Raju, and P. S. Roy, “The Development of Lifecycle Data for Hydrogen Fuel Production and Delivery,” A Research Report from the National Center for Sustainable Transportation, 2017. [Online]. Available: https://escholarship.org/content/qt3pn8s961/qt3pn8s961_noSplash_b1d302a49f54828e57a5e496836ad255.pdf?t=pnc577
- [72]J. Hua, C.-W. Cheng, and D.-S. Hwang, “Total life cycle emissions of post-Panamax containerships powered by conventional fuel or natural gas,” *Journal of the Air & Waste Management Association*, vol. 69, no. 2, pp. 131–144, Feb. 2019, doi: 10.1080/10962247.2018.1505675.
- [73]K. L. Tay *et al.*, “Numerical investigation on the combustion and emissions of a kerosene-diesel fueled compression ignition engine assisted by ammonia fumigation,” *Applied Energy*, vol. 204, pp. 1476–1488, Oct. 2017, doi: 10.1016/j.apenergy.2017.03.100.
- [74]H. Winnes and E. Fridell, “Particle Emissions from Ships: Dependence on Fuel Type,” *Journal of the Air & Waste Management Association*, vol. 59, no. 12, pp. 1391–1398, Dec. 2009, doi: 10.3155/1047-3289.59.12.1391.
- [75]US Energy Information Administration, “Annual Energy Outlook 2021.” US Energy Information Administration, 2021. [Online]. Available: <https://www.eia.gov/outlooks/aeo/assumptions/pdf/international.pdf>
- [76]Bunkerworld, “Bunkerworld Prices,” 2021. <https://www.bunkerworld.com/prices/> (accessed Apr. 06, 2021).
- [77]Hydrogen Council, “Path to hydrogen competitiveness|A cost perspective.” Hydrogen Council, 2020. [Online]. Available: https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
- [78]R. Michael Nayak-Luke and R. Bañares-Alcántara, “Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production,” *Energy & Environmental Science*, vol. 13, no. 9, pp. 2957–2966, 2020, doi: 10.1039/D0EE01707H.
- [79]Hydrogen Council, “Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness,” McKinsey, 2021. [Online]. Available: <https://hydrogencouncil.com/en/hydrogen-insights-2021/>
- [80]B. Fehrm, “Bjorn’s Corner: The challenges of Hydrogen. Part 15. Hydrogen cost,” *Leeham News and Analysis*, Nov. 13, 2020. <https://leehamnews.com/2020/11/13/bjorns-corner-the-challenges-of-hydrogen-part-15-hydrogen-production/> (accessed Sep. 09, 2021).

- [81]M. Fasihi, R. Weiss, J. Savolainen, and C. Breyer, “Global potential of green ammonia based on hybrid PV-wind power plants,” *Applied Energy*, vol. 294, p. 116170, Jul. 2021, doi: 10.1016/j.apenergy.2020.116170.
- [82]Ballard, “Fuel Cell Power Module for Heavy Duty Motive Applications.” 2016. [Online]. Available: https://www.ballard.com/docs/default-source/motive-modules-documents/fcvelocity_hd_family_of_products_low_res.pdf
- [83]T. Takaishi, A. Numata, R. Nakano, and K. Sakaguchi, “Approach to High Efficiency Diesel and Gas Engines,” *undefined*, 2008. /paper/Approach-to-High-Efficiency-Diesel-and-Gas-Engines-Takaishi-Numata/3b358426f86e2ae7c667878f7c3c1de1b6747e12 (accessed Mar. 03, 2021).
- [84]WÄRTSILÄ Corporation, “Wärtsilä 46F Engine.” WÄRTSILÄ Corporation, 2019. [Online]. Available: https://www.wartsila.com/docs/default-source/product-files/engines/ms-engine/wartsila-o-e-w-46f.pdf?utm_source=engines&utm_medium=dieselengines&utm_term=w46f&utm_content=brochure&utm_campaign=msleadscoring
- [85]WÄRTSILÄ Corporation, “Dual-fuel Engines– WÄRTSILÄ 20DF, 34DF, 46DF AND 50DF.” WÄRTSILÄ Corporation, 2015. [Online]. Available: <https://cdn.wartsila.com/docs/default-source/product-files/engines/df-engine/brochure-o-e-df-engines-2015.pdf?sfvrsn=6>
- [86]Anvil, “Ember,” 2021. <https://ember-climate.org/data/carbon-price-viewer/>