



Environmental impacts of fuel cell use in deep-sea shipping towards 2050

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HIGHLIGHTS

- The cargo capacity change affected by fuel cell propulsion systems is assessed.
- The long-term life cycle environmental impacts of fuel cell use in deep-sea shipping are quantified.
- Fuel cell decarbonization potential in shipping hinges on how clean the hydrogen supply is.
- Fuel cell use in deep-sea shipping can induce new environmental burdens.

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ABSTRACT

Fuel cells have the potential to reduce greenhouse gas (GHG) emissions from deep-sea shipping. To fully understand the environmental impacts of integrating fuel cells into deep-sea ships, this study evaluates the life cycle environmental impacts from 2020 to 2050 for two leading fuel cell systems: liquid hydrogen with proton exchange membrane fuel cells (liquid-H₂ PEMFC) and liquid ammonia with solid oxide fuel cells (liquid-NH₃ SOFC). The study covers various factors, including changes in cargo capacity, operation modes, developments in hydrogen production and electricity decarbonization. We examine two energy scenarios developed by the International Energy Agency: the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE). Our findings reveal that, under different ranges and speeds, the liquid-H₂ PEMFC results in a 2% increase to a 10% decrease in cargo weight, while the liquid-NH₃ SOFC leads to a 4%–23% decrease. By 2050, under the NZE scenario, liquid-H₂ PEMFC and liquid-NH₃ SOFC can reduce GHG emissions per tonne-nautical mile by 69%–75% and 65%–71%, respectively, compared to traditional ships. The use of fuel cells also introduces environmental trade-offs. This assessment can help policymakers gain a more comprehensive understanding of the role of fuel cells in reducing GHG emissions in deep-sea shipping and underscores the potential environmental challenges associated with their large-scale deployment in the future.

1. Introduction

International shipping is crucial to global trade, accounting for over 80% of the merchandise traded between countries [1]. However, the sector's dependence on heavy fuel oil (HFO) and marine gas oil (MGO) in internal combustion engines (ICE) has significant climate change impact. In 2022, international shipping was responsible for about 2% of global energy-related carbon dioxide (CO₂) emissions [2]. Additionally, it emits other pollutants such as nitrogen oxides, sulfur oxides, and

particulate matter, which harm both the environment and human health [3,4]. To mitigate the climate change, the International Maritime Organization (IMO) has proposed a target for the shipping industry to achieve net-zero life-cycle greenhouse gas (GHG) emissions by around 2050 [5]. Hydrogen (H₂) and ammonia (NH₃) used with fuel cells have the potential to reduce the hard-to-abate emissions from this sector [6,7].

However, the environmental performance of these emerging decarbonization solutions needs to be assessed from a life cycle perspective.

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This is crucial for understanding the technological suitability of these solutions and for defining the most effective implementation pathways [8–10].

Several life cycle assessment (LCA) studies have explored the use of fuel cells on ships. Lee et al. [11] quantified the environmental impacts of a nearshore ferry in South Korea equipped with a proton-exchange membrane fuel cell (PEMFC) using compressed H₂. They found that H₂ produced from natural gas via steam methane reforming results in higher greenhouse gas emissions compared to MGO burned in a diesel generator for the same round trip. Similarly, Hwang et al. [12] compared the environmental impacts of a coastal ferry completing a round trip using either liquid H₂ with a PEMFC or MGO with a diesel engine. They considered H₂ produced from natural gas and liquefied using various electricity sources. Their findings showed that the GHG emissions from using liquid H₂ could be either higher or lower than those from MGO, depending on the electricity source used for H₂ production and liquefaction. Focusing on the fuel origin, Perčić et al. [13] examined the environmental impacts of passenger ships powered by combinations of PEMFC and solid oxide fuel cell (SOFC) systems using liquid H₂ and liquid NH₃ from fossil fuels, carbon capture and storage, and renewables in Croatian coastal waters. The study concluded that fuel cell systems using blue and green H₂ and NH₃ generally have lower environmental impacts compared to diesel-powered ships. Given the potential for a significant influx of new ships powered by alternative fuels and propulsion technologies in the future, Kanchiralla et al. [14] evaluated the environmental impacts of a RoPax ferry (i.e., a vessel that combines passenger cabins with a roll-on/roll-off decks) traveling between Sweden and Germany in 2030, using liquid H₂-PEMFC and liquid NH₃-SOFC, with fuel production sourced from onshore wind. Their results indicated that while these solutions could reduce GHG emissions, they also present environmental trade-offs related to human toxicity and freshwater ecotoxicity associated with wind energy infrastructure. Kanchiralla et al. [15] further compared the environmental impacts of adopting these fuel cell systems across different vessel types, including a RoPax ferry, a tanker, and a service vessel, by 2030.

Existing research primarily focuses on short-sea shipping, leaving a gap in understanding the environmental impacts of fuel cell systems for deep-sea shipping, where GHG emissions are challenging to reduce through direct electrification. In practice, several fuel cell short-sea ships are currently in operation or under construction, despite the considerable cost challenges associated with fuel cell systems [16,17]. With the development of standards and regulations for fuel cells in maritime transportation worldwide, large-scale commercial application and cost reductions may become possible [17]. Additionally, the effects of changes in cargo capacity and energy consumption due to the substitution of propulsion systems have not been systematically explored. Furthermore, factors such as efficiency improvements, regional differences, and the evolving market dynamics of H₂ production over time are overlooked. Broader socio-economic developments also influence the environmental impacts of emerging technologies. To address these gaps, this paper develops life-cycle models for the operation of a typical containership powered by both traditional and fuel cell propulsion systems. These models integrate changes in cargo capacity and energy consumption resulting from the replacement of conventional systems with fuel cell propulsion, along with future global H₂ production and electricity decarbonization scenarios, enabling assessment of the environmental impacts per unit of transport work (the amount of cargo transported over a certain distance) from 2020 to 2050. The main contributions of this paper are twofold. First, the assessment provides valuable insights for deploying fuel cell systems in deep-sea shipping and minimizing their environmental impacts from a long-term perspective. Second, the comprehensive LCA framework developed in this paper lays a foundation for assessing the environmental performance of fuel cell use across the entire shipping sector.

2. Methods and data

The LCA conducted in this study follows the standardized guidelines of ISO 14040: 2006 [18]. The main steps include goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment, and interpretation of results. For the LCI analysis, processes within the system boundary are divided into foreground (see Sections 2.2.1–2.2.6) and background processes (see Section 2.2.7). In the foreground processes, energy, material, and infrastructure inputs as well as emissions are collected from existing literature or calculated. These inventory data are then classified into specific environmental impact categories and the corresponding impacts are quantified using characterization factors.

2.1. Goal and scope

As shown in Fig. 1, this study aims to quantify the cradle-to-grave environmental impacts of operating three types of containerships: one powered by HFO in an ICE, another by liquid H₂ in a PEMFC, and the third by liquid NH₃ in a SOFC. The analysis spans from 2020 to 2050 and is conducted using an attributional LCA approach. The functional unit is the transportation of one tonne of cargo weight over a distance of one nautical mile (t-nm). The analysis focuses on a typical large containership with a capacity of 8749 TEU (20-ft equivalent units). Containerships with a capacity of 8000 to 11,999 TEU were the largest source of GHG emissions in 2018, accounting for 25% of total emissions [19]. They are also projected to have the largest share of the global containership fleet by 2050, reaching up to 20% [19].

To comprehensively assess the impacts of different ship operation modes and broader energy transitions on environmental indicators, this study considers various ship operation scenarios, including range, operation speed (see Section 2.1.1), and future H₂ supply scenarios aligned with different policy settings (see Section 2.2.2). It also incorporates background data reflecting electricity decarbonization under different scenarios (see Section 2.2.7).

2.1.1. Ship design and operation scenarios

Fuel cell propulsion systems vary in both volumetric and gravimetric energy densities, depending on the type of fuel cell and fuel tank used. These variations influence cargo capacity in terms of available space and weight compared to conventional ships. For long-distance vessels, the size of the fuel tank plays a crucial role and is determined by the ship's designed range—a longer range requires a larger tank, which can reduce cargo capacity. Speed also matters, as slower speeds reduce energy consumption for the same range [20], allowing for a smaller fuel tank. Any change in cargo capacity directly affects fuel consumption per transport work, which in turn impacts the ship's environmental performance.

To quantify the environmental impacts of different propulsion system designs and operating conditions, various scenarios covering ship range, operating speed, and refueling frequency are established in this study. As detailed in Table 1, the container ship operates on the Asia-Europe route, specifically between Shanghai and Rotterdam, covering a distance of 11,000 nautical miles. This is one of the main routes for the case ship. The round trip is technically feasible and represents a high fuel demand scenario. Stopping at ports for refueling lowers the amount of fuel that needs to be carried, though increased stops lead to higher operational costs due to port charges and time spent at the dock. A single interim port call is thus assumed to represent the low fuel demand scenario, with the shorter voyage falling within the range of the case ship. Additionally, this study also evaluates results based on an average service speed of 20 nautical miles per hour (i.e., knots) [21] and a reduced speed of 16 knots [22].

2.2. Life cycle inventory analysis

In this section, we present the unit process data for ship production,

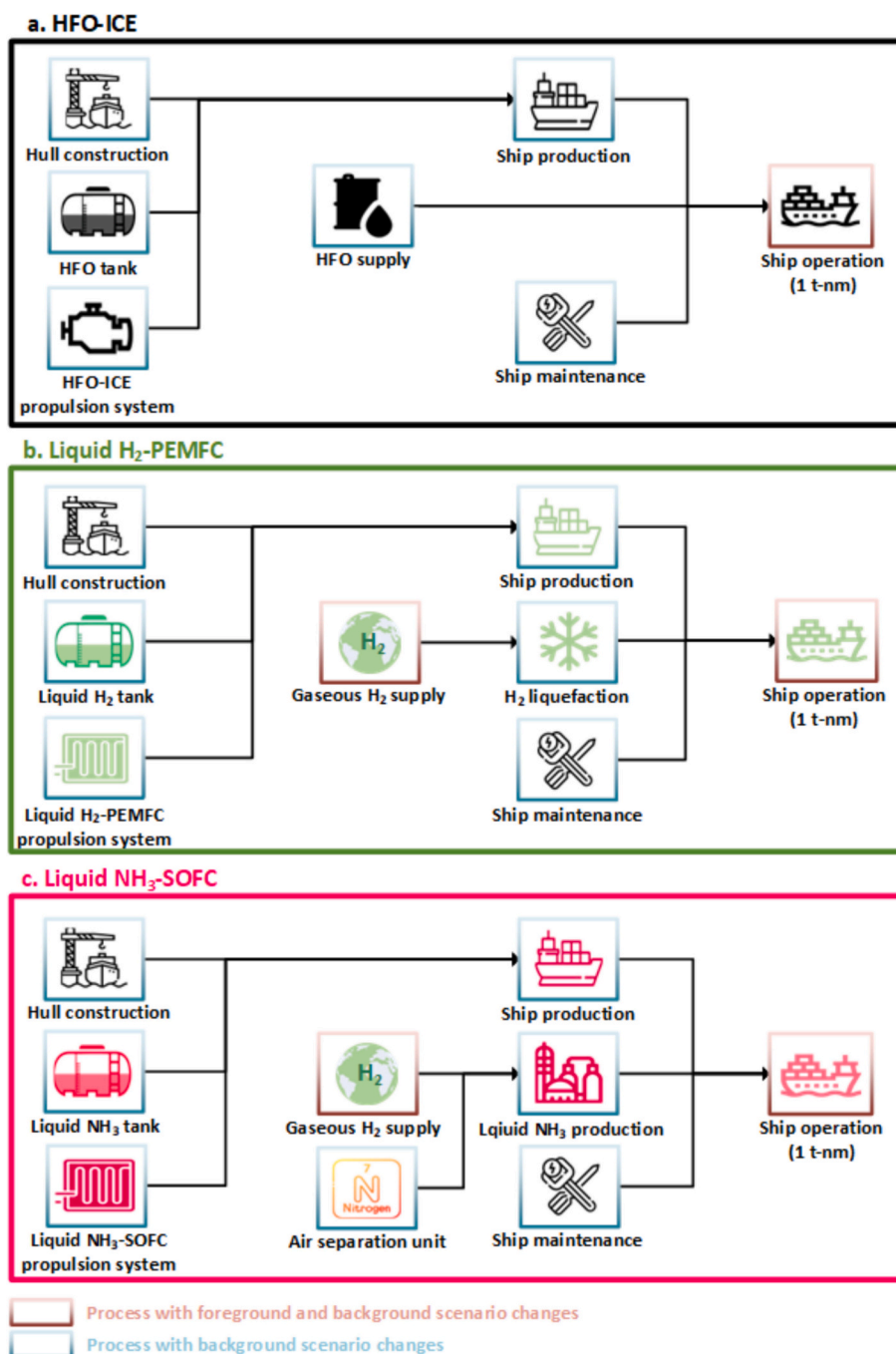


Fig. 1. Simplified system boundaries of container shipping powered by different power systems.

Table 1
Ship design and operation scenarios.

Scenario	R-A-N	R-L-N	S-A-N	S-L-N	S-A-I	S-L-I
Range	22,000 nm	22,000 nm	11,000 nm	11,000 nm	5500 nm	5500 nm
Trip	Return	Return	Single	Single	Single	Single
Speed	20 knots	16 knots	20 knots	16 knots	20 knots	16 knots
Stops to refuel	Nonstop	Nonstop	Nonstop	Nonstop	1	1

fuel supply, and ship operation. Detailed LCI can be found in Section 1 of the Supporting Information (SI).

2.2.1. Ship construction

The material composition for constructing the container ship is determined by the lightweight tonnage (LWT), calculated using Eq. 1, and material breakdowns from Jain et al. [23] and Notten et al. [24]. The material demand for the main and auxiliary engines is excluded at this stage, with its detailed LCI collected separately. Welding, electricity, heat usage, and emissions during hull construction are also calculated based on the methodology outlined by Notten et al. [24].

$$LWT = (1 - \lambda) \times \frac{DWT}{\lambda} \tag{1}$$

where *LWT* represents the weight of the empty vessel [25]; dead-weight tonnage (*DWT*) refers to the vessel's load capacity, which includes cargo, fuel, water, crew and their belongings [26], 103800 t [21];

λ is the ratio of DWT to the ship's total weight, 70% [27]. Here, using the HFO ship as a proxy, the LWT (with the weight of the main and auxiliary engines excluded following Jain et al. [23]) is used to estimate the weight of the hull, outfitting and other machinery, hereafter referred to as the hull weight. It is assumed that the ship's hull weight remains constant across ships powered by different propulsion systems. The production of the various propulsion systems is modeled separately, and the differences in weight and volume between the new fuel cell systems and the HFO system affect the cargo capacity.

2.2.2. H₂ supply

The H₂ supply models are taken from our previous study Wei et al. [28]. This study integrates two prospective global H₂ production models from the International Energy Agency: the Stated Policies (STEPS) Scenario and the Net Zero Emissions by 2050 (NZE) Scenario. These models account for nine leading technologies: coal gasification, natural gas steam reforming, biomass gasification (with and without carbon capture and storage (CCS)), and grid-coupled water electrolysis using alkaline

electrolyzers, proton exchange membrane electrolyzers, and solid oxide electrolysis cells. The models also take into account electricity decarbonization, efficiency improvements, advancements in electrolyzer technology, and shifts in the H₂ production mix.

2.2.3. HFO and H₂-based fuel supply

Based on the LCI of HFO supply from the ecoinvent database [29], a desulfurization process from Silva [30] is incorporated to reduce the sulfur content in HFO from 1.03% [29] to 0.5%, in order to meet the global sulfur limit outside Sulfur Emission Control Areas (SECAs) mandated by the IMO 2020 regulation [31]. Although HFO with a sulfur content below 0.1% is required within SECAs, fuel switching is not considered in this study, as voyages through these areas account for only a small fraction of the total journey. For the liquid H₂ and NH₃, the LCI of gaseous H₂ from the global market, which represents the weighted average of 15 regional markets, is sourced from Wei et al. [28]. For the production of liquefied H₂, the inputs for the H₂ liquefaction plant and the associated H₂ losses are sourced from Wulf and Zapp [32]. The

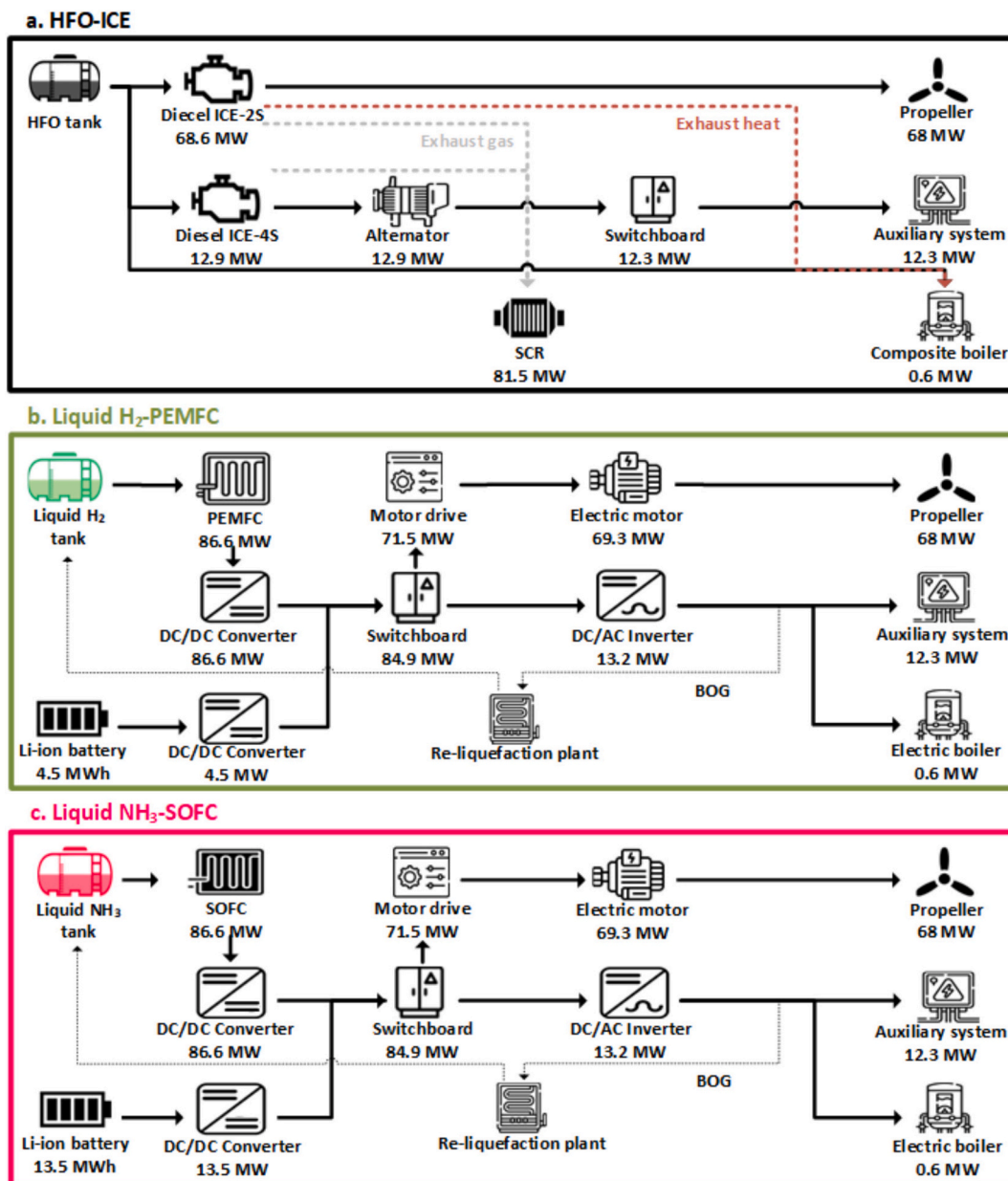


Fig. 2. Components and their dimensions for different propulsion systems.

median electricity consumption of 10.5 kWh to produce one kg liquified H₂ is used [33]. The LCI for liquid NH₃ is taken from D'Angelo et al. [34].

2.2.4. Propulsion systems

The components of traditional and fuel-cell propulsion systems differ substantially, with each system's components sized to deliver equivalent output power to the propeller and auxiliary systems. Fig. 2 shows the workflow, components, and dimensions of HFO-ICE and fuel cell systems. In the HFO-ICE system, the propeller is mechanically driven by a two-stroke diesel ICE. A four-stroke auxiliary ICE is coupled with an alternator to meet the onboard electricity demand. Exhaust gases from both the main and auxiliary ICEs are treated by a selective catalytic reduction (SCR) system to lower nitrogen oxides emissions, ensuring compliance with IMO Tier III regulations. Urea is used as a reducing agent to convert nitrogen oxides into diatomic nitrogen and water [14]. The catalyst in the SCR system, primarily composed of TiO₂, makes up about 0.25% of the SCR's weight [35], and the catalyst must be replaced once during the ship's lifetime [14]. In the HFO-ICE system, a composite boiler is installed to recover the exhaust heat from the main ICE and meet the heat demand. In fuel cell systems, H₂ or NH₃ is directly used to generate electricity through electrochemical redox reactions, which then drive the electric motor and propeller. Since fuel cells supply direct current, it must be converted into alternating current for use in the auxiliary systems and the electric boiler. In fuel cell systems, a battery storage system is included to handle transient operations and provide cold-start power due to the slow response of fuel cells [36]. The battery is sized to support 10 min of operation at 20% load for PEMFCs and 30 min at the same load for SOFCs [15]. This difference reflects the higher operating temperature of SOFCs, which results in slower start-up and response times compared to the lower-temperature PEMFCs [37]. In addition, a reliquefaction plant is installed on fuel cell ships to manage boil-off gas (BOG) (see Section 2.2.5 for details). Components such as the PEMFC, SOFC, inverter and battery, which have shorter lifespans than the ship itself, need to be replaced several times over the ship's operational lifetime.

Key parameters and the LCI sources for these components are listed in Table 2. For the LCI related to motor drive manufacturing, material data is sourced from Westberg [38], and electricity consumption data is supplemented from the manufacturer [39].

2.2.5. Fuel storage

The HFO is stored in normal diesel tanks. Liquid H₂ and NH₃ are stored in cryogenic tanks. The properties of these fuels, their storage requirements, and the associated LCI sources are summarized in Table 3.

Table 2

The key technical parameters of various propulsion systems. In this table, the superscripts in the component column (a, b, c) represent the components required for the HFO-ICE, liquid H₂-PEMFC, and liquid NH₃-SOFC propulsion systems, respectively.

Component	Efficiency (%)	Lifespan (years)	Mass factor (t/MW(h))	Volume factor (m ³ /MW(h))	Key parameters source	LCI source
Diesel ICE (Main) ^a	50	25	29.2	27.5	[15,40]	[14]
Diesel ICE (Aux) ^a	48	25	29.2	27.5	[15,40]	[14]
Alternator ^a	96	25	2.5	5.0	[14,40]	[29]
Shafting ^a	99	25	–	–	[41,42]	[24]
SCR ^a	–	25	0.9	5.0	[43,44]	[14]
PEMFC ^b	55	6	3.3	5.7	[15,36]	[45]
SOFC ^c	60	5	45.3	97.2	[15,36]	[15]
Converter (for fuel cell) ^{b,c}	98	25	2.3	5.1	[46–48]	[29]
Motor drive ^{b,c}	97	25	1.1	4.4	[49–51]	[38,39]
Electric motor ^{b,c}	98	25	2.7	4.2	[14,52,53]	[29]
Inverter ^{b,c}	98	6	3.7	9.0	[54–56]	[29]
Battery ^{b,c}	96	11	5.9	3.3	[10,36,57]	[29]
Converter (for battery) ^{b,c}	98	25	3.0	6.7	[36,46,47]	[29]
Switchboard ^{a,b,c}	99.8	25	0.7	1.4	[58–60]	[24]
Composite boiler ^a	85	25	3	8.8	[61,62]	[29]
Electric boiler ^{b,c}	99	25	3	8.8	[62,63]	[64]

2.2.6. Ship operation

To complete the same voyage with different propulsion systems and operation scenarios, the corresponding on-board energy demand is determined by the Eq. 2:

$$E_{ij} = \left(\frac{P_{AM_i}}{\eta_{M_i}} + \frac{P_{AA}}{\eta_{A_i}} + \frac{P_{AB}}{\eta_{ABS_i}} \right) \times T_j \times FM \quad (2)$$

where E_{ij} is the total onboard energy demand for one voyage, given the propulsion system i and operation scenario j , MWh; P_{AM_i} , P_{AA} (as defined in Eq.3–4 [19]) and P_{AB} are the average output power of the main engine under scenario j , the auxiliary engine and the auxiliary boiler, respectively, MW; η_{M_i} , η_{A_i} and η_{ABS_i} represent the efficiencies of the main engine, auxiliary engine and the auxiliary power system i , respectively. In the HFO-ICE system, the auxiliary boiler can utilize exhaust heat, whereas in fuel cell systems, electricity is required to power it; T is the sailing time in hours for operation scenario j , determined by the voyage length and average operating speed; FM is the fuel margin, set at 120% [71].

$$P_{AM_i} = \frac{P_M \times \left(\frac{D_{Ave}}{D_{Max}} \right)^{\frac{2}{3}} \times \left(\frac{S_{Ave_j}}{S_{Max}} \right)^3}{\eta_w \times \eta_f} \quad (3)$$

where P_M is the installed power of the main engine, MW; D_{Max} and D_{Ave} are the maximum and average draught of the ship, respectively; S_{Max} is the maximum operating speed of the ship, and S_{Ave_j} is the average operating speed under scenario j ; η_w and η_f denote weather and fouling correction factors (0.867 and 0.917 respectively [19]).

$$P_{AA} = P_A \times LF_A \quad (4)$$

where P_A is the installed power of the auxiliary engine, MW; and LF_A is the average load factor of the auxiliary engine, set at 50% [13].

As liquid H₂ and NH₃ are stored in cryogenic tanks, the boil-off gas (BOG) may occur due to heat ingress. A conservative assumption is made that a reliquefaction process is used to ensure better control and more effective management of BOG [72]. The reliquefaction system is designed based on the maximum hourly BOG volume, and the additional energy required for BOG reliquefaction is calculated using Eq. 5.

$$E_{R_{ij}} = \frac{k_{R_{ij}}}{\lambda_{A_i}} \times \sum_{t=0}^{T-1} \left[\left(\frac{E_{ij}}{\rho_i} - \frac{E_{ij} \times t}{\rho_i \times FM \times T} \right) \times BOG_i \right] \quad (5)$$

where $E_{R_{ij}}$ is the energy demand for reliquefying BOG, in MWh; $k_{R_{ij}}$ is the electricity consumption for reliquefying the BOG of propulsion system i under operation scenario j , assumed as 3.3 kWh/kg for liquid H₂ [73]

Table 3

The key technical parameters and data source of various fuels and their storage.

Fuel	Lower heating value (MWh/t)	Gravimetric energy density including tank (MWh/t)	Volumetric energy density including tank (MWh/m ³)	Data source	LCI of fuels	LCI of tanks
HFO	11.9	10.1	10.1	[65]	[29]	[66]
Liquid H ₂	33.3	5.6	1.3	[65]	[28,32,33]	[67]
Liquid NH ₃	5.2	4.2	2.9	[65,68]	[28,34]	[69,70]

and 0.224 kWh/kg for liquid NH₃ [74]; t is time point of ship operation in one voyage, in hours; ρ_i is the energy density for fuel used in propulsion system i ; and BOG_i is the hourly evaporation rate of the fuel used in propulsion system i , assumed as 0.0167% per hour for liquid H₂ and 0.0017% per hour for liquid NH₃ [75].

In addition to the varying volume and mass of fuel and tanks required to meet the energy demands of different propulsion systems, the installed power, volume, and mass of components in fuel cell propulsion systems differ from those in traditional systems. Consequently, these differences lead to changes in cargo space and weight, as shown in Eq. 6 and 7.

$$\Delta V_{ij} = \beta \times V_{OE} + V_{OT} + V_{OO} - \alpha \times V_{FC_i} - \frac{E_{ij} + E_{R_{ij}}}{V_{FT_i}} - V_{FO_i} \quad (6)$$

where ΔV_{ij} represents the change in cargo space change due to the adoption of fuel cell propulsion system i in scenario j , measured in m³; β is the ratio of the engine room volume to the HFO-ICE main engine volume (V_{OE}), which is 5 times larger due to clearances required for access and maintenance [76]; V_{OT} is the volume of the existing HFO tank, 12000 m³; V_{OO} is the total volume of other necessary components in the HFO-ICE propulsion system, m³; α is the ratio of the engine room to the volume of the fuel cell in fuel cell propulsion system i (V_{FC_i}), which is 2 times larger because fuel cells consist of many small modules, significantly reducing the space needed for maintenance and repair [76]; V_{FT_i} is the volumetric energy density of the fuel (including tank) used in the propulsion system i ; V_{FO_i} is the total volume of other components in the fuel cell propulsion system i .

$$\Delta M_{ij} = M_{OE} + M_{OT} + \frac{E_{ij}}{G_O} + M_{OO} - M_{FC_i} - \frac{E_{ij} + E_{R_{ij}}}{G_{FT_i}} - M_{FO_i} \quad (7)$$

where the ΔM_{ij} represents the change in cargo weight due to replacing the HFO-ICE propulsion system with the fuel cell propulsion system i in the scenario j , measured in t; M_{OE} is the mass of the HFO main engine; M_{OT} is the mass of the existing HFO tank; G_O is the gravimetric energy density of HFO; M_{OO} is the total mass of other components in the HFO-ICE system; M_{FC_i} is the mass of the fuel cell in the fuel cell system i ; G_{FT_i} is the gravimetric energy density of the fuel (including tank) used in the fuel cell propulsion system i ; M_{FO_i} is the total mass of other components in the fuel cell propulsion system i .

Finally, the fuel consumption per t-nm is decided by the energy demand leaving the fuel margin, voyage length and resulting cargo weight. The operation parameters corresponding to the fuel used in different propulsion systems are listed in Table 4.

2.2.7. Background scenarios

To address the temporal mismatch between foreground and background data and to account for future developments in key sectors, prospective LCI background databases are used. These are derived from the ecoinvent v3.8 database (system model "Allocation, cut-off by classification") [29] and the latest version of the REMIND model [82], utilizing the open-source Python library premise v1.5.8 [83]. The REMIND model provides global future scenarios based on shared socioeconomic pathways (SSPs) and representative concentration pathways. For the STEPS and NZE scenarios, two prospective LCI databases are employed: SSP2-NDC (projecting approximately 2.5 °C warming by

Table 4

Operation parameters of different propulsion systems.

Propulsion systems	HFO-ICE [77–80]		Liquid-H ₂ PEMFC [15]	Liquid-NH ₃ -SOFC [15]
	Main engine	Aux engine	PEMFC	SOFC
Engine type				
Specific fuel consumption (g/kWh)	178.6	186.0	54.6	320.5
Urea ^a (g/kWh)	14.4	9.6	–	–
CH ₄ (g/kWh)	0.009	0.009	–	–
CO (g/kWh)	0.9	1.0	–	–
CO ₂ (g/kWh)	585	605	–	–
NO _x (g/kWh)	3.4	2.6	–	0.003
N ₂ O (g/kWh)	0.029	0.030	–	–
NH ₃ (g/kWh)	0.026	0.026	–	–
NMVOG (g/kWh)	0.424	0.441	–	–
PM ₁₀ (g/kWh)	0.051	0.053	–	–
PM _{2.5} ^b (g/kWh)	0.581	0.605	–	–
SO ₂ (g/kWh)	1.795	1.869	–	–

^a The HFO-ICE is equipped with an SCR unit, using a 40 wt% urea solution to reduce NO_x emissions.

^b PM_{2.5} is assumed to make up 92% of PM₁₀ [81].

2100) and SSP1-PkBudg500 (projecting approximately 1.3 °C warming by 2100). These databases include updated electricity inventories, reflecting changes in regional electricity mixes and efficiencies for technologies such as carbon capture and storage, and photovoltaic panels [84].

LCI modeling and LCA calculations are performed by an open-source software, the Activity Browser [85]. Multiple foreground scenarios and prospective LCI background databases are integrated by the super-structure approach [86].

2.3. Life cycle impact assessment

The climate change impact is quantified based on the IPCC AR5 characterization factors of global warming potentials with a time horizon of 100 years [87]. We add characterization factors for the uptake and release biogenic CO₂ (−1 and +1 respectively), which is needed to account for technologies such as bioenergy with CCS, and H₂ (+11), as H₂ may leak into the air and act as an indirect greenhouse gas [88]. We also quantify other 15 environmental impacts by the method of Environmental Footprint (EF) v3.0 [89]. The specific information for the environmental indicators is listed in Table 5.

3. Results and discussion

3.1. Cargo space and weight loss

As shown in Fig. 3, the cargo space and weight loss vary depending on the voyage and speed scenarios. Although fuel cell systems have a lower volumetric energy density compared to the HFO-ICE system, the cargo space loss from switching to fuel cell propulsion is relatively minor due to their high energy efficiency. In the S-A-N scenario, both liquid H₂-PEMFC and liquid NH₃-SOFC exhibit similar cargo space losses, at 7% and 4%, respectively. For a round trip, cargo loss can reach up to 20%

Table 5
The specific information for environmental impact categories.

Environmental impact	Unit	Method	Reference
Climate change	kg CO ₂ -eq	IPCC	[87,88]
Acidification	mol H + -eq	EF v3.0	[89]
Ecotoxicity: freshwater	CTUe	EF v3.0	[89]
Resource use: energy carriers	MJ	EF v3.0	[89]
Eutrophication: aquatic freshwater	kg P-eq	EF v3.0	[89]
Eutrophication: aquatic marine	kg N-eq	EF v3.0	[89]
Eutrophication: terrestrial	mol N-eq	EF v3.0	[89]
Human toxicity: cancer effects	CTUh	EF v3.0	[89]
Human toxicity: cancer effects	CTUh	EF v3.0	[89]
Ionizing radiation: human health	kBq U ²³⁵	EF v3.0	[89]
Land use	dimensionless	EF v3.0	[89]
Resource use: minerals and metals	kg Sb-eq	EF v3.0	[89]
Ozone depletion	kg CFC-11-eq	EF v3.0	[89]
Particulate matter	disease incidences	EF v3.0	[89]
Photochemical ozone formation	kg NMVOC-eq	EF v3.0	[89]
Water use	kg world eq. deprived	EF v3.0	[89]

and 9% for these two fuel cell systems in the R-A-N scenario, respectively. PEMFCs have a significantly smaller volume and weight compared to ICE and SOFC systems due to their lower operating temperature (80–100 °C) [90]. When interim refueling is available during a

voyage, the liquid H₂-PEMFC system leads to negligible cargo space loss in the S-A-I scenario and none in the S-L-I scenario. Although the liquid NH₃-SOFC system can use a smaller tank compared to the HFO-ICE system in the S-A-I and S-L-I scenarios, it still occupies 1% of cargo space because of the lower volumetric density of the SOFC system. It should be noted that although cargo space loss is significant, unlike the cargo weight constraint, it can be alleviated by placing tanks on the deck [91,92].

Across all scenarios, the liquid H₂-PEMFC system results in less cargo weight loss compared to the liquid-NH₃ SOFC system due to its higher gravimetric energy density for on-board storage and lighter fuel cell system. In the R-A-N scenario, liquid H₂-PEMFC and liquid NH₃-SOFC reduce the cargo weight by 10% and 23%, respectively. In general scenarios, such as the S-A-N scenario, the cargo weight capacity with these systems is 2% and 12% lower than that of a traditional ship, respectively. If interim port calls are available during a voyage (S-A-I scenario), the liquid H₂-PEMFC system can increase the cargo weight by 1%, whereas the liquid NH₃-SOFC system results in a 6% reduction in cargo weight. When operating at a lower speed, liquid H₂-PEMFC and liquid NH₃-SOFC systems can reduce cargo weight loss by approximately 1%–4% and 2%–9%, respectively, compared to operating at the average speed.

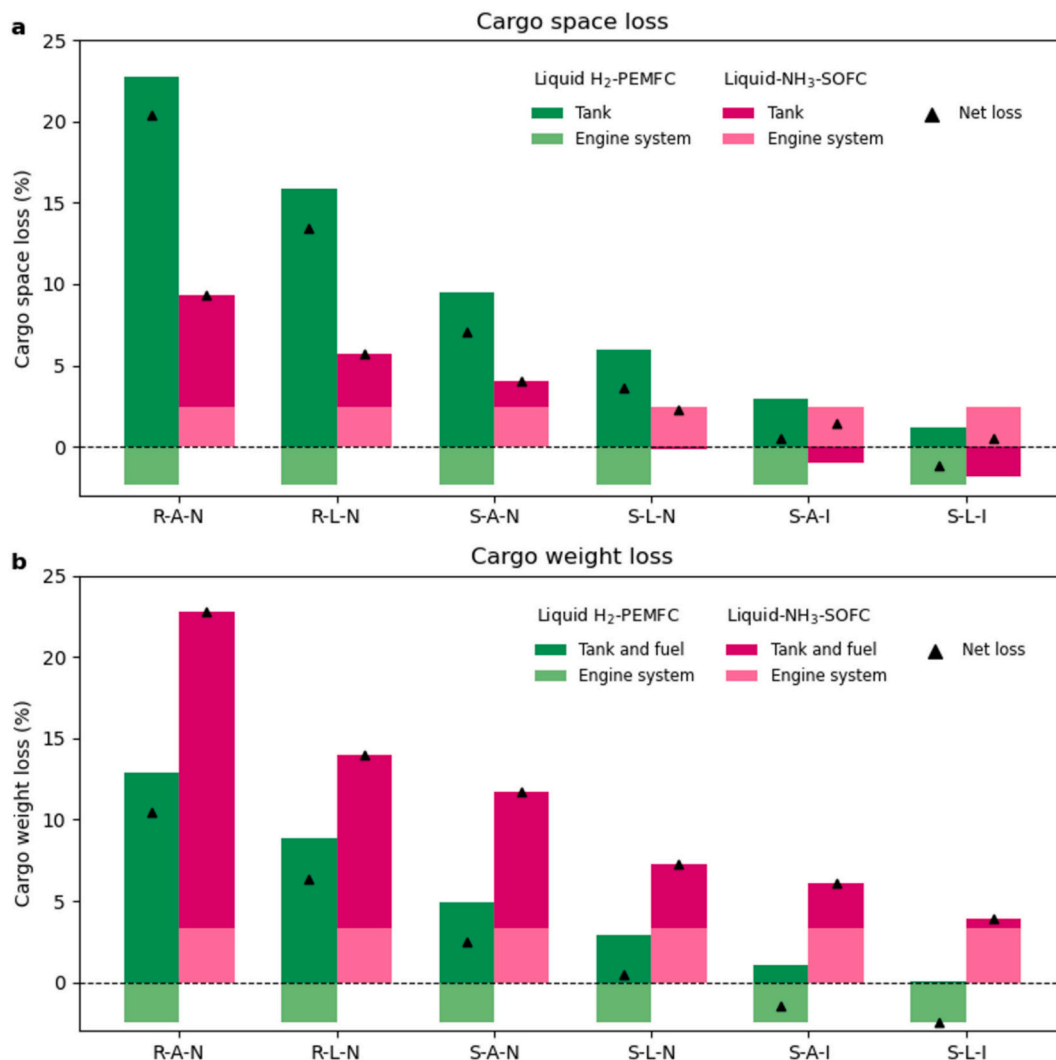


Fig. 3. The cargo space and weight losses associated with fuel cell propulsion systems compared to traditional propulsion systems. In this figure, R-A-N = 22,000 nm-20 knots-Nonstop, R-L-N = 22,000 nm-16 knots-Nonstop, S-A-N = 11,000 nm-20 knots-Nonstop, S-L-N = 11,000 nm-16 knots-Nonstop, S-A-I = 5500 nm-20 knots-1 refueling stop, and S-L-I = 5500 nm-16 knots-1 refueling stop. The net loss is the sum of the loss caused by the tank and fuel, as well as the engine system.

3.2. Global prospective GHG emissions

The prospective GHG emissions of ship transport using traditional ICE versus fuel cell systems are shown in Fig. 4. Currently, fuel cell systems are less effective at decarbonizing deep-sea shipping due to the reliance on fossil fuels, such as natural gas steam reforming and coal gasification, for H₂ production. Additionally, the carbon-intensive electricity used in H₂ liquefaction and liquid NH₃ production significantly contributes to emissions. As a result, the GHG emissions from fuel cell systems are currently about double those of traditional systems. In the STEPS scenario, while electricity decarbonization by 2050 reduces GHG emissions from liquid H₂ and NH₃ production, the H₂ production mix remains largely unchanged, preventing a reduction in overall emissions compared to traditional ships. However, in the NZE scenario, where H₂ production shifts substantially to water electrolysis (61% of the H₂ market) powered by low-carbon electricity by 2050 [93], fuel cell systems can achieve substantial GHG emissions reductions compared with traditional ones. In this scenario, the GHG emissions from fuel cell systems are around 5–8 g CO₂-eq per t-nm. Liquid H₂-PEMFC ships and liquid NH₃-SOFC ships can reduce the GHG emissions by 69–75% and 65–71%, respectively, compared to traditional ships. The liquid H₂-PEMFC system shows slightly lower GHG emissions compared to the liquid NH₃-SOFC system due to the higher gravimetric energy density of liquid H₂ storage and the lighter fuel cell system. Aligning with IMO's 2050 net-zero target, the IMO Net-Zero Framework (NZF), a mandatory regulation, was approved in principle in April 2025. It introduces GHG fuel intensity (GFI) targets requiring ships to reduce their emission intensity on a well-to-wake basis by 4–30% (Tier 2: Base target) and 17–43% (Tier 1: Direct compliance target) during the period 2028–2035, compared with the 2008 reference value of 93.3 g CO₂-eq per MJ. A 2040 base target has also been set, representing a 65% reduction from the reference value [94]. The well-to-wake emissions of fuel cell systems primarily originate from the fuel supply stage. Liquid H₂-PEMFC ships could meet the base and direct compliance targets by 2032 and 2035, respectively, whereas liquid NH₃-SOFC ships could only meet the base target by 2034 (see Table S43 in the SI for detailed data).

Although the use of fuel cell propulsion systems results in a loss of cargo capacity, this is not the primary factor in determining their effectiveness in decarbonizing deep-sea shipping. In the NZE scenario, the GHG emissions from ships powered by fuel cell systems are similar by 2050, regardless of the ranges represented by the R-A-N, S-A-N, and S-A-I scenarios. Even with interim port calls for refueling, the reduction in GHG emissions due to alleviated cargo capacity loss is not significant. Reducing operational speed, as demonstrated in the R-L-N, S-L-N, and S-L-I scenarios, can lead to a decrease in GHG emissions of about 25% for HFO-ICE ships, 19–22% for liquid H₂-PEMFC ships, and 25–31% for liquid NH₃-SOFC ships compared to the average speed by 2050 in the NZE scenario.

In addition to sourcing H₂ from markets, stakeholders in the shipping sector can utilize green H₂ produced from newly established renewable capacities. However, there is significant uncertainty around the supply capacity of green H₂ due to the competing demand for renewable energy. To quantify the potential GHG emissions reduction, we further modeled a scenario with 100% renewable fuel supply. In this case, H₂ is assumed to be produced entirely by PEM electrolyzers powered by onshore wind. The electricity used for H₂ liquefaction and liquid NH₃ production is also sourced from onshore wind. If the entire fuel supply chain is powered by 100% onshore wind, both liquid H₂-PEMFC and liquid NH₃-SOFC ships could achieve the direct compliance GFI target from the start of the NZF's implementation. By 2050, GHG emissions could be reduced by 83–88% for liquid H₂-PEMFC ships and 82–86% for liquid NH₃-SOFC ships compared to HFO-ICE ships. The GHG emissions from fuel cell ships are approximately 2–4 g CO₂-eq per t-nm. Therefore, prioritizing the decarbonization of H₂ production is crucial for reducing GHG emissions in the shipping sector through fuel cell systems. While reducing speed is an effective supplementary strategy, the primary focus

should be on transitioning to cleaner H₂ production.

3.3. Regional prospective GHG emissions

The rate of change in H₂ production mix and electricity decarbonization varies across different regions, which affects the GHG emissions from H₂-based fuel supply. To quantify this impact on the GHG emissions of ship operations, this study also models the H₂-based supply in China, the Middle East, and the European Union (EU), where refueling might occur along the case route. Based on the S-A-I scenario, Fig. 5 presents the GHG emissions of fuel cell ships powered by liquid H₂ and NH₃, broken down by H₂ market and various H₂ sources in the three regions mentioned above. As H₂ markets across three regions currently rely on fossil fuels, fuel cell ships in 2020 do not reduce GHG emissions compared to HFO ships, regardless of the refueling location. Their GHG emissions are about 1.3 to 2.5 times higher than those of HFO ships across the three regions. China shows the highest GHG emissions due to its coal-dominated H₂ production and electricity generation mix. The Middle East and the EU have lower GHG emissions, as their H₂ is primarily produced from natural gas. By 2050, in the STEPS scenario, fuel cell ship emissions are expected to decrease mainly due to electricity decarbonization. Although water electrolysis is included in current policies, fossil fuel-based H₂ will still account for at least 87% across three regions. Therefore, decarbonizing ships with fuel cells remains challenging under current policies. Only liquid H₂-PEMFC ships refueled in the EU are expected to slightly reduce GHG emissions compared to HFO-powered ships, primarily due to the lower GHG emissions associated with the electricity and H₂ production mix in that region. In the NZE scenarios, by 2050, fuel cell ships are expected to substantially reduce GHG emissions compared to HFO ships, regardless of refueling location. Although there are regional variations in the H₂ production mix, the GHG emissions from fuel cell ships refueled in different regions are fairly consistent, averaging about one-third of those from HFO ships, at around 6–8 g CO₂-eq per t-nm.

Regarding the GHG emissions of fuel cell ships by H₂ sources, clear regional differences are observed for each H₂ source in 2020. At present, fuel cells powered by fossil fuel-based H₂ such as coal gasification and natural gas steam reforming cannot reduce GHG emissions compared to HFO. This remains true even when fossil fuel-based H₂ production is equipped with CCS, although there is a slight reduction in the EU due to its cleaner electricity mix compared to other regions. At the same time, fuel cells using H₂ from water electrolysis produce 1.8–5.7 times higher GHG emissions than HFO across the three regions, owing to fossil fuel-dominated electricity mixes. Currently, except for China, H₂ from biomass gasification can reduce GHG emissions for fuel cell ships compared to HFO. When biomass gasification is combined with CCS, fuel cell ships can even achieve negative emissions. However, it should be noted that biomass-based H₂ will play only a marginal role in H₂ production even by 2050 [93]. By 2050, the GHG emissions of fuel cells using the same H₂ source become similar across different regions. Under both the STEPS and NZE scenarios, fuel cells using fossil-based H₂ with CCS and those using electrolytic H₂ show significant GHG emissions reductions due to electricity decarbonization. For fuel cells using H₂ from coal gasification and natural gas steam reforming with CCS, emissions could be reduced by 22–48% and 35–57%, respectively, compared to HFO across the three regions in the NZE scenario. Fuel cells using H₂ from water electrolysis present an even greater GHG emissions reduction potential compared to HFO, achieving at least a 74% reduction across the three regions by 2050 in the NZE scenario. Among electrolysis technologies, SOEC exhibits higher GHG emissions compared to AE and PEM due to the additional heat required in H₂ production [28]. These results highlight that ship operations between different regions have varying GHG emissions potential. For fuel cell ship operations, optimizing refueling port selection is key to maximizing GHG emissions reduction potential.

On 1 January 2025, FuelEU Maritime entered into force, setting

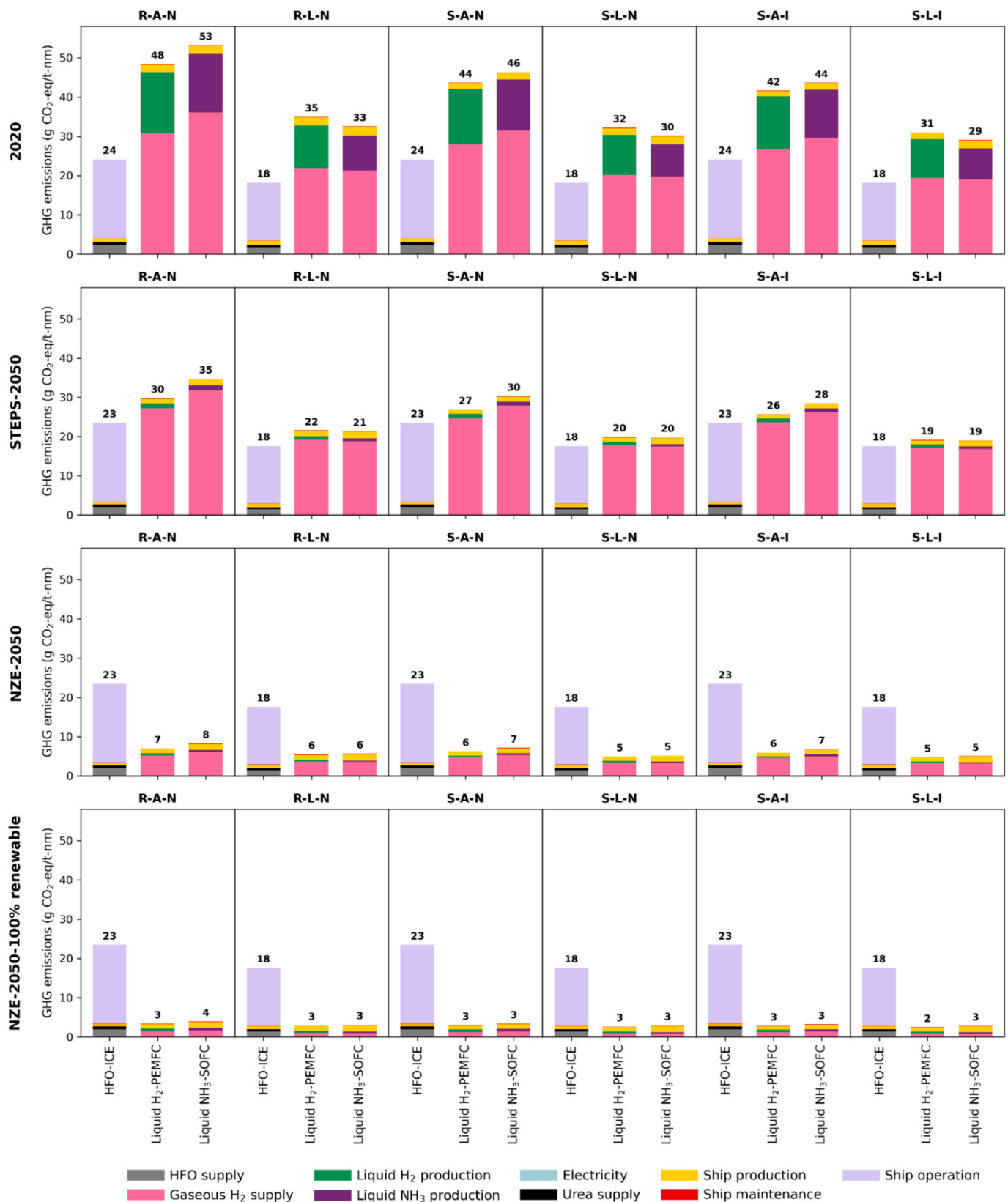


Fig. 4. The process contribution to the GHG emissions of different ships in different scenarios. For the liquid H₂ production and liquid NH₃ production, the gaseous H₂ supply is a part of them and presented separately. In this figure, R-A-N = 22,000 nm-20 knots-Nonstop, R-L-N = 22,000 nm-16 knots-Nonstop, S-A-N = 11,000 nm-20 knots-Nonstop, S-L-N = 11,000 nm-16 knots-Nonstop, S-A-I = 5500 nm-20 knots-1 refueling stop, and S-L-I = 5500 nm-16 knots-1 refueling stop.

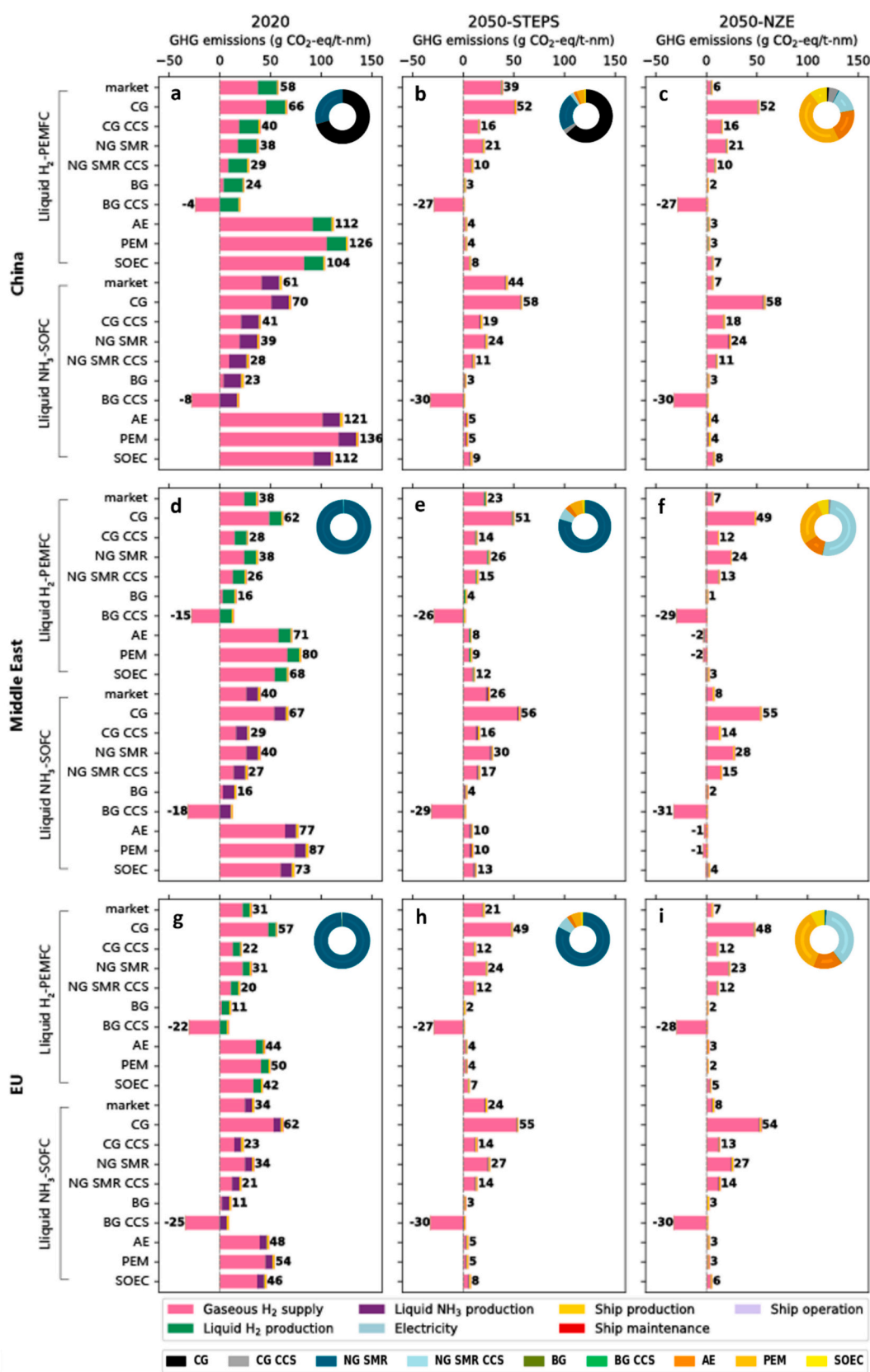


Fig. 5. GHG emissions from ship operations fueled at ports in different regions under the S-A-I scenario (5500 nm-20 knots-1 refueling stop). Subplots a–c show the results for China in 2020, 2050 under the STEPS scenario, and 2050 under the NZE scenario. Subplots d–f show the results for the Middle East, and subplots g–i show the results for the EU. In this figure, the doughnut charts represent the gaseous H₂ production mix for China, the Middle East and the EU. CG = coal gasification, NG SMR = steam methane reforming of natural gas, BG = biomass gasification, CCS = carbon capture and storage, AE = alkaline electrolyzer, PEM = proton exchange membrane electrolyzer and SOEC = solid oxide electrolysis cell.

requirements on the annual average GHG intensity of energy used by ships above 5000 gross tonnage trading within the EU or European Economic Area (EEA). Using 91.16 g CO₂-eq/MJ as the 2020 reference value, the regulation starts with a 2% reduction in 2025, increases to 6% in 2030, and accelerates after 2035 to reach an 80% reduction by 2050 [95]. We further compare the well-to-wake emissions of fuel cells refueled in different regions with FuelEU Maritime requirements (see Table S44 in the SI for detailed data). Based on H₂ market developments in different regions under the NZE scenario, fuel cell ships refueled in

China and the Middle East could meet the FuelEU Maritime requirements from 2035, whereas those refueled in the EU could meet the requirements from 2030. However, the presence of fossil fuel-based H₂ with CCS in the market may prevent compliance by 2050. Regarding different H₂ sources, only H₂ from biomass could enable fuel cell ships to meet the requirements consistently from 2025 to 2050. H₂ produced via water electrolysis using AE and PEM technologies could meet the requirements continuously from 2030 to 2050 in the EU, and from 2035 to 2050 in China and the Middle East. Fossil fuel-based H₂ with CCS across

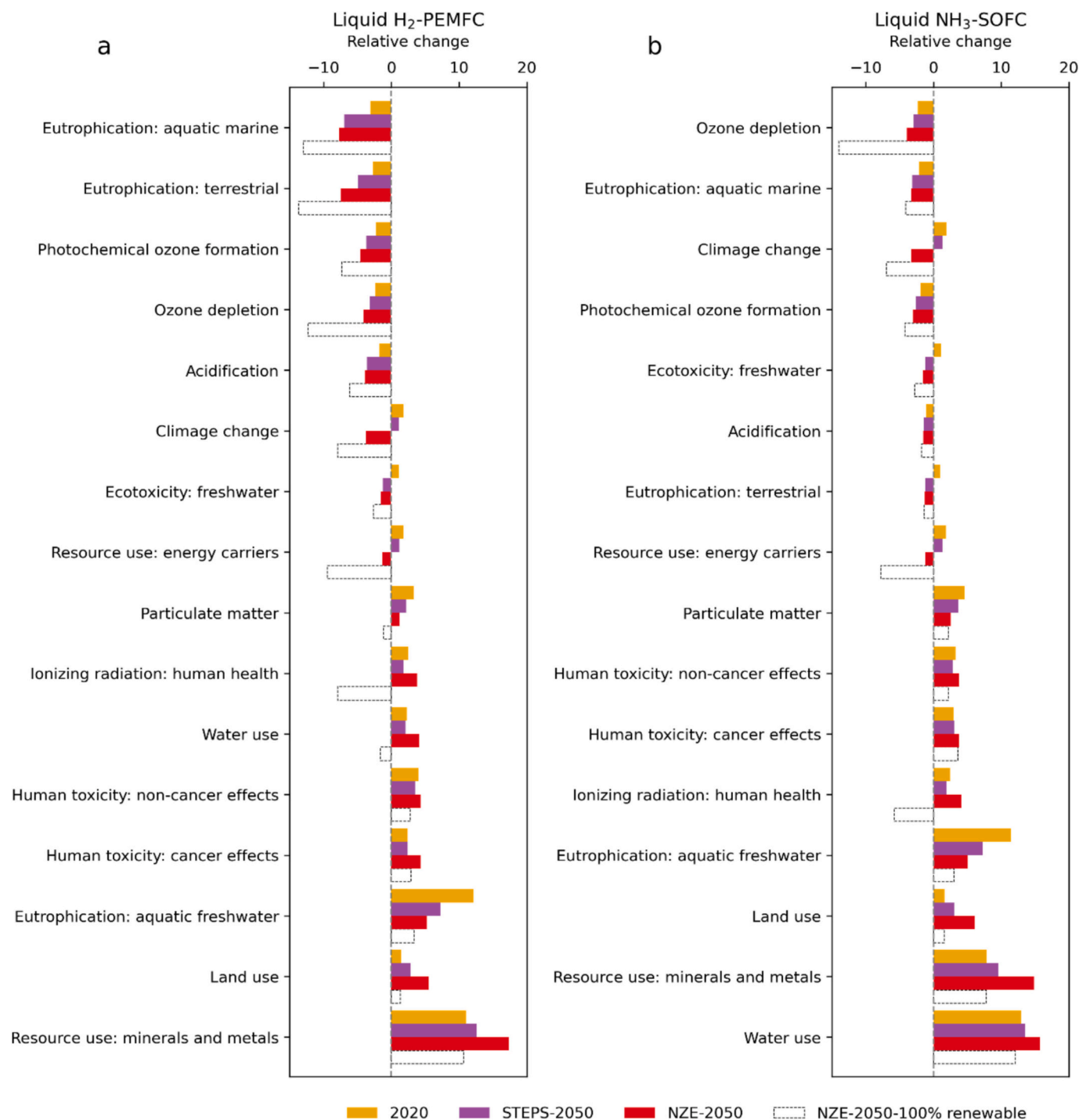


Fig. 6. The relative environmental impacts of fuel cell systems compared to traditional ones from 2020 to 2050 under the S-A-N (11,000 nm-20 knots-Nonstop) scenario. (a) Liquid H₂-PEMFC ship compared under the 2020, STEPS-2050, NZE-2050, and NZE-2050-100% renewable scenarios. (b) Liquid NH₃-SOFC ship compared with the HFO ship under the 2020, STEPS-2050, NZE-2050, and NZE-2050-100% renewable scenarios. The values indicate the factors of change in the environmental impact of fuel cell ships compared to HFO-powered ships.

different regions could help fuel cell ships comply before 2040.

Under the IMO NZF or FuelEU Maritime regulations, the portion of annual average GHG emissions that exceeds the required GFI will incur additional costs, either through the purchase of Remedial Units (RUs) or through penalties, respectively. Under the IMO NZF, the initial RU prices for the reporting periods between 2028 and 2030 are 100 USD/CO₂-eq for Tier 1 compliance deficits and 380 USD/CO₂-eq for Tier 2 [94]. For FuelEU Maritime, the penalty for non-compliance from 2025 is 640 EUR/CO₂-Eq. [96]. In addition, since shipping is covered by the EU Emissions Trading System (EU ETS), companies must purchase sufficient EU allowances by auction to cover all GHG emissions from 2026, with the average allowance price being about 65 EUR/CO₂-eq in 2024 [97,98]. Under the EU ETS, 100% of emissions from voyages and port calls within the EU or EEA and 50% of emissions from voyages into or out of the EU or EEA are subject to compliance [99]. These external costs may accelerate the adoption of fuel cell ships when H₂-based fuels become sufficiently low-carbon. At the same time, the European Commission has launched the European Hydrogen Bank auction that uses emissions trading revenues to support producers of renewable H₂ in the form of a fixed premium [100]. By bridging the gap between renewable H₂ production costs and the price that consumers are willing to pay, the cost of using renewable H₂-based fuels can be further reduced and the potential market for fuel cell ships can be expanded.

3.4. Prospective environmental impacts

Using fuel cell propulsion systems for deep-sea ships can yield both benefits and trade-offs for other environmental indicators. As shown in Fig. 6, in 2020, ships powered by liquid H₂-PEMFC have lower impacts on marine and terrestrial eutrophication, photochemical ozone formation and acidification compared to HFO-ICE ships, due to the absence of nitrogen oxides and sulfur oxides emissions during operation. Additionally, because liquid H₂ production involves fewer hydrocarbons emissions than HFO, the liquid H₂-PEMFC ships also have a lower impact on ozone depletion. The liquid NH₃-SOFC ships offer similar environmental benefits, except for terrestrial eutrophication, due to higher NH₃ and nitrogen oxides emissions during liquid NH₃ production. In the STEPS scenario, as electricity decarbonizes by 2050 with a decline in coal power and its associated emissions of aluminum and nitrogen oxides, environmental benefits extend to reductions in freshwater ecotoxicity for liquid H₂-PEMFC, and to reductions in freshwater ecotoxicity and terrestrial eutrophication for liquid NH₃-SOFC compared to the HFO ship. In the NZE scenario, as electricity and H₂ production become more decarbonized, fuel cell ships are expected to further decrease the aforementioned environmental impacts and fossil fuel use compared to traditional ships by 2050. In a 100% renewable scenario, fuel cell ships can significantly reduce ionizing radiation compared to traditional ships by 2050.

Future fuel cell systems to power ships will continue to face environmental challenges related to minerals and metals use, land use, water use, ionizing radiation, human toxicity, freshwater eutrophication and particulate matter. Fig. S2 further illustrates the contributors to these environmental trade-offs. As the adoption of renewable electricity and water electrolysis expands, some environmental impacts associated with fuel cell ships may worsen. For the minerals and metals use, copper in electricity distribution networks, copper in PEMFCs, and gold in the electronic equipment of liquid NH₃ plants contribute to a higher impact for fuel cell ships compared to traditional ones. In the future, the demand for rare earth metals—such as neodymium, dysprosium, and praseodymium for wind power; tellurium and indium for solar panels; and iridium and platinum for electrolyzers [101,102]—in gaseous H₂ production will become another main driver. For land use, electricity consumption in liquid H₂ and NH₃ production causes fuel cell ships to have a higher impact than traditional ones currently, mainly due to coal-fired electricity and the operation of associated coal mines. In the future, the installation of new infrastructure such as photovoltaic facilities and

electrolyzers associated with liquid H₂ and NH₃ supply will significantly increase this impact for fuel cell ships. For water use, coal-dominated electricity in H₂ liquefaction causes liquid H₂-PEMFC ships to have a higher impact compared to the traditional ones. Liquid NH₃-SOFC ships have a higher water use impact compared to liquid H₂ PEMFC ships due to the water cooling requirements in NH₃ production, where evaporation occurs in the water tower. The water use impact of fuel cell ships increases as water electrolysis for H₂ production expands. However, the absolute water consumption for these fuel cell ships is not well-defined and can be assumed to be significantly lower than that of irrigated agriculture. For ionizing radiation, carbon-14 released during the treatment of low-level radioactive waste via plasma torch incineration in petroleum production contributes to the impact associated with HFO ships. For fuel cell ships, this impact is linked to the scale of nuclear power in the electricity mix. As the share of nuclear power decreases in the future, electricity consumption in liquid H₂ and NH₃ production contributes less to this impact. However, gaseous H₂ supply will become the main contributor as the share of water electrolysis in the H₂ market increases. For human toxicity with cancer effects, carcinogenic emissions—such as chromium and hexavalent chromium from low-alloy and stainless steel production for ship structures—are the main contributors. The liquid H₂ and NH₃ tanks lead to a higher impact for fuel cell ships compared to traditional ones. As the share of coal-fired electricity—which also produces hexavalent chromium during hard coal ash treatment—decreases in the electricity mix, the contribution from liquid H₂ and NH₃ production declines. In contrast, the contribution from gaseous H₂ supply increases as water electrolysis expands, due to the substantial demand for steel used in electricity equipment. For human toxicity with non-cancer effects, the main contributors for HFO ships are chloride, lead, and mercury emissions during HFO production, as well as CO emissions during ship operation. For fuel cell ships, intensive electricity use in water electrolysis and PEMFC construction both require large amounts of copper and are associated with lead, arsenic, arsenic ions, and cadmium emissions, thereby worsening human toxicity with non-cancer effects. Nevertheless, the contribution from liquid H₂ and NH₃ processes decreases as coal-fired electricity, which has higher arsenic ion and cadmium emissions, is replaced by renewables.

In contrast, as coal use declines during the energy transition, associated emissions of phosphate and particulate matter smaller than 2.5 μm are also reduced, thereby mitigating freshwater eutrophication and particulate matter formation, respectively. However, the production of copper, steel, multi-silicon wafers, and aluminum for wind turbines and solar panels still generates associated emissions, resulting in higher freshwater eutrophication and particulate matter formation impacts from fuel cell ships compared to HFO-powered ones. The nitrogen oxides and NH₃ emissions during liquid NH₃ production result in a higher particulate matter impact for liquid NH₃-SOFC ships compared to liquid H₂-PEMFC ships, as these emissions can contribute to particulate matter formation [103,104].

The environmental trade-offs of reducing GHG emissions with fuel cell systems are broadly consistent across regions with the global trend, with detailed results provided in Section 2.2 of the SI. It should be noted that results presented for environmental categories not directly related to climate change should not be over-interpreted, as much of the data in this study is focused on GHG emissions. Moreover, technological advancements and waste management strategies to mitigate other environmental impacts were not considered. Our findings aim to highlight areas for further investigation and potential improvement. Finally, we conduct a sensitivity analysis on main parameter assumptions, including fuel cell efficiency, fuel cell lifespan, battery lifespan, and BOG rates of H₂-based fuel on-board storage. The sensitivity analysis shows that improvements in fuel cell efficiency have the greatest impact on all environmental indicators and can be considered an effective way to mitigate the environmental impacts of fuel cell ships. Extending the lifespan of fuel cells shows a low sensitivity for certain environmental indicators, while the impacts of changes in battery lifespan and BOG rates are

negligible (see Section 2.3 in the SI for details).

4. Conclusions

This study quantifies the life cycle environmental impacts of fuel cell-powered ships from 2020 to 2050, examining the effects of cargo capacity changes due to propulsion system replacements, operational modes, and broad energy scenarios. The analysis evaluates the GHG emission reduction potential and other environmental impacts under two future trajectories for global H₂ production technology and mix: the current policy settings (STEPS) and the goal of achieving net zero CO₂ emissions by 2050 (NZE), as outlined by the IEA. The findings provide insights into the potential environmental trade-offs of adopting fuel cells for decarbonizing deep-sea shipping from a long-term perspective, helping policymakers make informed decisions and minimize the environmental impacts of fuel cell ships. The main conclusions are summarized as follows:

The liquid H₂-PEMFC system causes less cargo space loss in short-range operations and consistently results in smaller cargo weight loss for deep-sea ships compared to the liquid NH₃-SOFC system. In various operational modes, the liquid H₂-PEMFC system can either increase cargo space by up to 1% or decrease it by up to 20%. In contrast, the liquid NH₃ SOFC system consistently reduces cargo space by 1% to 9%. When an interim port is available, the liquid-H₂ PEMFC system has a lesser impact on cargo volume compared to the liquid NH₃ SOFC system. Regarding cargo weight, the liquid H₂-PEMFC system can increase it by up to 2% or decrease it by up to 10%, while the liquid NH₃-SOFC system typically results in a decrease of 4% to 23%. Despite the higher energy efficiency of the SOFC, its larger mass and the lower gravimetric energy density of the liquid NH₃ storage system reduce cargo weight more significantly than the liquid H₂-PEMFC system.

Fuel cells can reduce GHG emissions by up to 75% compared to traditional ships by 2050 in the NZE scenario and by 88% in a 100% renewable scenario. Fuel cell ships currently cannot facilitate the decarbonization of deep-sea shipping due to the fossil fuel-dominated energy supply. While lower speeds and interim refueling can somewhat reduce GHG emissions, these measures alone are insufficient to make fuel cell ships have lower GHG emissions compared to traditional HFO-ICE ships. In the STEPS scenario, this remains true by 2050. In the NZE scenario, where H₂ production shifts to water electrolysis powered by low-carbon grid electricity, liquid H₂-PEMFC and liquid NH₃-SOFC ships can reduce GHG emissions by 69%–75% and 65%–71%, respectively, by 2050 compared to HFO-ICE ships. Establishing a 100% renewable fuel supply chain can further enhance their reduction potential to 83%–88% and 82%–86%, respectively. The GHG emissions of fuel cell ships refueled in different regions show significant variations due to different paces of the energy transition. This underscores the critical need to prioritize the decarbonization of H₂ production and to carefully select refueling regions to effectively decarbonize the shipping sector.

The environmental impacts of fuel cell ships should be further minimized. Using fuel cells to decarbonize deep-sea shipping can bring co-benefits by reducing impacts such as marine and terrestrial eutrophication, photochemical ozone formation, ozone depletion, acidification, freshwater ecotoxicity and fossil fuel use compared to traditional ships. However, it also introduces new environmental burdens, including those related to minerals and metals use, water use, land use, freshwater eutrophication, human toxicity, ionizing radiation, and particulate matter. Some of these impacts become more severe as the H₂ production mix shifts to water electrolysis powered by renewables. This calls for comprehensive technological improvements and enhanced waste management measures in the fuel production phase to minimize these environmental impacts.

Fuel cell ships could see gradual adoption after 2030 if H₂ production is sufficiently decarbonized. Achieving substantial GHG emissions reductions from shipping through fuel cell deployment relies

on the H₂ market transitioning as rapidly as projected in the IEA's NZE scenario. For H₂ production, scaling up water electrolysis technologies such as AE and PEM electrolysis powered by low-carbon electricity represents a scalable and safer long-term pathway. Under the NZE scenario, and from the perspective of complying with both IMO NZF and FuelEU Maritime regulations, the EU could adopt both liquid H₂-PEMFC and liquid NH₃-SOFC ships from 2030, while China and the Middle East may adopt liquid H₂-PEMFC ships from around 2035. Liquid H₂-PEMFC ships hold an advantage in regulatory compliance due to their lower GHG emissions compared with liquid NH₃-SOFC ships. In addition, policy instruments such as carbon pricing on ship emissions and premiums for renewable H₂ production outside the EU could also be introduced to support the gradual uptake of fuel cell ships.

Future work outlook. In this paper, leading H₂ technologies, as foreseen by the IEA, are used as the basis for producing liquid H₂ and NH₃ and are assessed. Other emerging technologies, such as photo-catalytic water splitting (currently with very low conversion efficiency but amenable to scale-up) [105,106] and methane pyrolysis (currently at a low technology readiness level but with potential for rapid expansion) [107], can also be investigated. In addition, this paper focuses on informing policymakers about the future environmental impacts of using fuel cell systems in deep-sea shipping. Further research can examine the economic feasibility of fuel cell shipping by conducting cost comparisons between fuel cell ships and conventional ones. Separate studies could also investigate market acceptance of fuel cell ships.

Declaration of generative AI in scientific writing.

During the preparation of this work the author(s) used OpenAI/ChatGPT in order to polish the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRedit authorship contribution statement

Shijie Wei: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fayas Malik Kanchiralla:** Writing – review & editing, Methodology. **Henk Polinder:** Writing – review & editing, Methodology. **Frederik Schulte:** Writing – review & editing, Methodology. **Arnold Tukker:** Writing – review & editing, Supervision, Conceptualization. **Bernhard Steubing:** Writing – review & editing, Supervision, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apenergy.2026.127666>.

Data availability

The data used in this study are provided in the Supporting Information.

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Glossary

- AE:** Alkaline electrolyzer
BG: Biomass gasification
BOG: Boil-off gas
CCS: Carbon Capture and Storage
CG: Coal gasification
CO₂: Carbon dioxide
DWT: Deadweight tonnage
EEA: European Economic Area
EF: Environmental Footprint
EU: European Union
EU ETS: EU Emissions Trading System
GHG: Greenhouse gas
GFI: GHG fuel intensity
HFO: Heavy fuel oil
H₂: Hydrogen
ICE: Internal combustion engines
IMO: International Maritime Organization
LCA: Life cycle assessment
LCI: Life cycle inventory
LWT: Lightweight tonnage
MGO: Marine gas oil
NG SMR: Steam methane reforming of natural gas
NH₃: Ammonia
NZE: Net Zero Emissions by 2050 Scenario
NZF: IMO Net-Zero Framework
PEM: Proton exchange membrane electrolyzer
PEMFC: Proton exchange membrane fuel cell
SCR: Selective catalytic reduction
SECAs: Sulfur Emission Control Areas
SOEC: Solid oxide electrolysis cell
SOFc: Solid oxide fuel cell
SSPs: Shared Socioeconomic Pathways
STEPS: Stated Policies Scenario
TEU: 20-ft equivalent units