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Green hydrogen as an alternative fuel for the shipping industry

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There is growing pressure to reduce greenhouse gas (GHG) emissions from maritime transportation. One of the most effective strategies for reducing GHG emissions is to switch from conventional fuels such as heavy fuel oil to alternative fuels. Green hydrogen is a promising alternative for the shipping industry. Nonetheless, its potential usage will depend on more than its environmental friendliness. Economic, technical, and safety factors must be assessed. This paper provides a critical assessment of the potential usage of green hydrogen in the shipping industry with an evaluation of production routes, techno-economic performance, storage, and safety. Benchmarking is also carried out compared to existing 'grey' and 'blue' production routes specific to shipping industry applications. Important metrics for liquid hydrogen are analyzed to evaluate production cost and GHG emissions for various routes. Furthermore, a comparison is made for the safety and health issues of hydrogen compared to conventional and emerging maritime shipping fuels.

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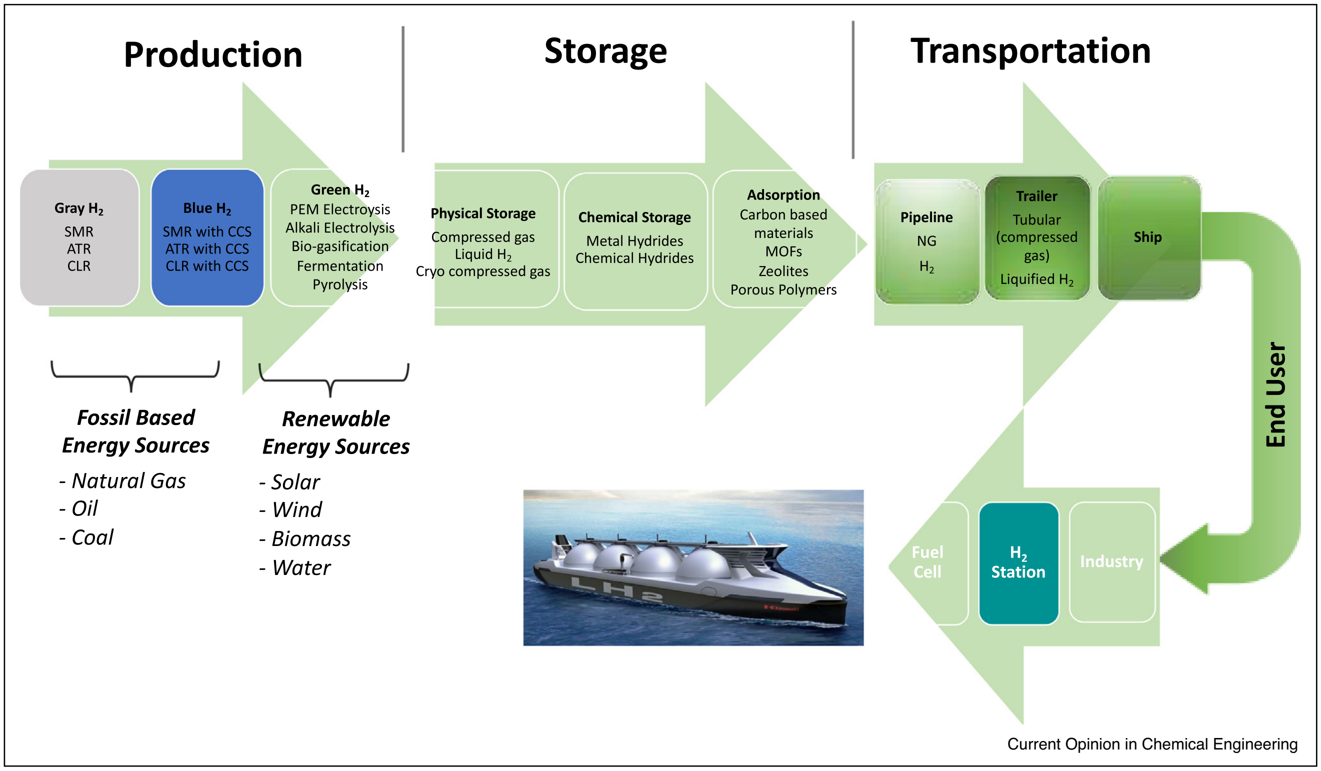
Introduction

Sustainable and scalable energy sources that provide high energy density are urgently needed as alternatives to secure the energy supply and to lessen the environmental impact of the current state-of-the-art non-renewable energy sources [1–3]. This challenge is particularly important for the maritime shipping industry which accounts for 7–8% of the global GHG emissions. In 2018, the International Maritime Organization (IMO) adopted the IMO Initial Strategy for reducing GHG emissions from international shipping consistent with the Paris Agreement (COP 21). The goals are quite ambitious with a call to reduce carbon emissions by at least 40% by 2030 ('2030 Goal') while aiming for 70% by 2050 relative to the 2008 emissions. Amongst the potential alternative energy sources, hydrogen is considered a promising fuel especially because of its environmental impact. When it burns it has zero carbon emission and depending on its production route, the amount of carbon dioxide that is released into the atmosphere can be lowered drastically [4–6]. The global hydrogen market is expected to grow from 70 million tonnes in 2019 to 120 million tonnes in 2024 [7,8]. Depending on the raw materials and production route, hydrogen is classified as grey, blue, and green. Grey hydrogen is obtained via the reforming of fossil fuels [9,10]. Over 95% of the global hydrogen is produced via reforming of fossil sources with about half of that amount coming from steam reforming of natural or shale gas [7,11,12]. When carbon emissions are captured, stored, or used (e.g. dry reforming [13]), hydrogen is designated as blue. Finally, green hydrogen corresponds to the use of a renewable feedstock and a renewable source of energy for the conversion of raw materials and the operation of the processing facility. For the production of grey and blue hydrogen, the environmental impact is considerably high and CO_2 emissions are around 830 million tonnes CO_2eq per year globally [12,14]. On the other hand, there are several renewable energy sources to produce green hydrogen such as wind, solar, nuclear, hydropower, geothermal, and biomass [3]. Among the renewable sources that are considered to produce hydrogen, wind and solar energies are most commonly used for hydrogen production up to date [15,16]. Most of the methods for the production of green hydrogen consider obtaining hydrogen either through water splitting reactions (e.g. water electrolysis, water thermolysis, photocatalytic water splitting, and thermochemical water splitting) or via dehydrogenation of hydrogen carrier molecules [17]. The world's largest green hydrogen plant has been planned to build to operate with a capacity of 650 ton/day hydrogen production by using electrolysis and 4 GW of renewable energy from solar, wind, and storage in 2025 [18,19]. In this paper, environmental and techno-economic impacts of hydrogen

Figure 1



Route of hydrogen production (via different energy sources) to end-use.

production technologies by using renewable and fossil-based energies have been compared with the specific focus on the utilization of these fuel sources in the shipping industry. Furthermore, different types of fuel and their hazardous/safety characteristics have also been considered.

Green hydrogen production

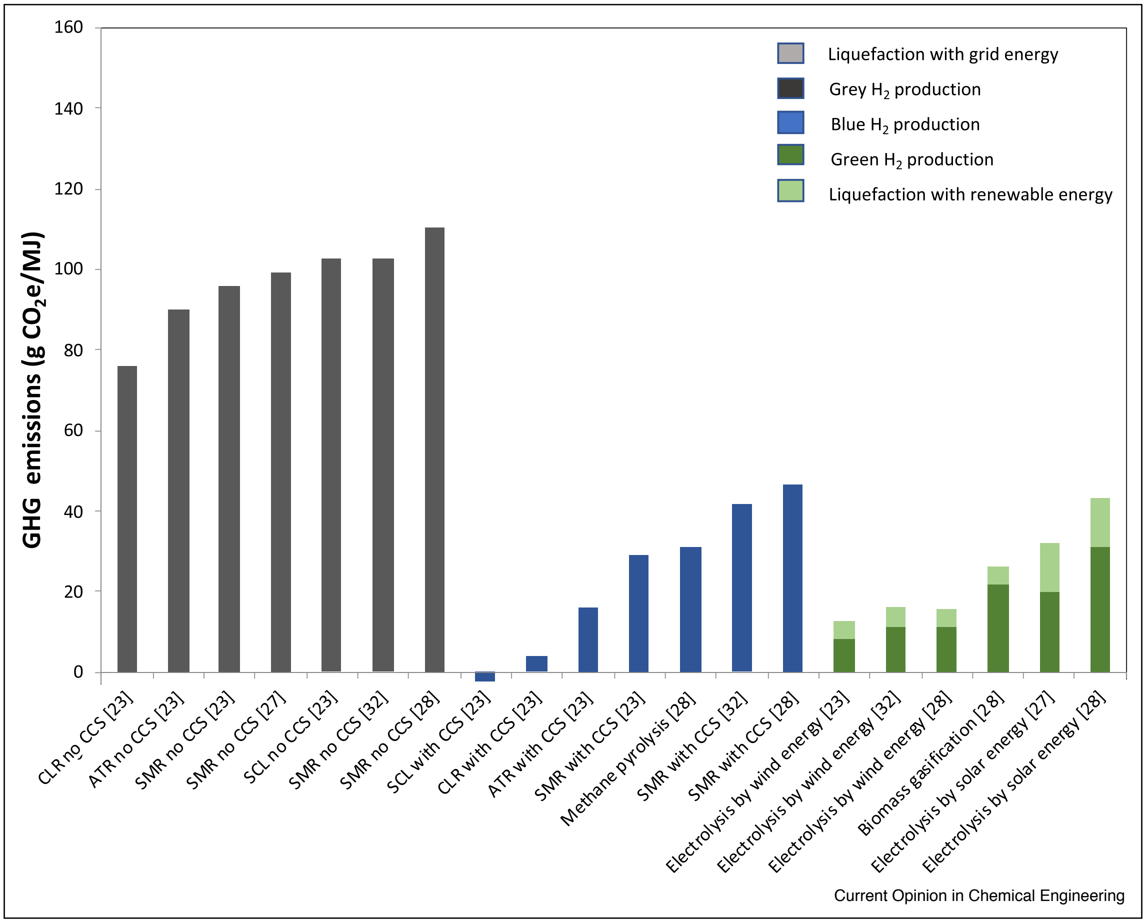
In a process for the production of green hydrogen, required power is obtained from CO_2-low/neutral alternative energy sources such as solar or wind. However, there are some technological hurdles to be addressed to make this approach feasible from both engineering and economic aspects [20]. Since the dependency on the grid is eliminated in the blue process, the cost increases significantly as the electrolysis process requires high electricity demand. Thus, the cost of the electricity production from solar and wind becomes the critical cost determining parament, which has come down spectacularly in the past decade a lot faster than experts forecasted and is an indicator of the future value of the electricity cost that will be obtained from such resources. Once the breakdown of the cost of the green hydrogen production is analyzed, the top share goes to the cost of electrolysis. The high cost of the electrolysis hinders the wide-scale implementation of this technique. However, as the advancement in materials and other technical issues will enable to overcome the issues that are related to this approach, the cost of green production will be lowered approximately 70% during the next decade and thus it will enable the widespread implementation of green hydrogen production approach.

Relatively novice production methods that include green route technologies have their cost-related disadvantages currently due to their limited implementation. However, their 'environmental cost' is much lower in comparison to blue or grey-based technologies, which makes the industry to consider green technologies for hydrogen production as next-generation fuel [21,22] (Figure 1).

Techno-economic evaluation and environmental impact assessment

The cost and environmental impact of producing LH_2 depend mainly on the type of raw materials, the conversion technology, the source of energy, the use of process (mass and energy) integration, and the extent of carbon sequestration and utilization within the process. Figure 2 summarizes the key findings of several studies on GHG emissions for different routes to produce grey, blue, and green hydrogen. The use of carbon capture and utilization reduces the GHG emissions but increases the cost. For

Figure 2

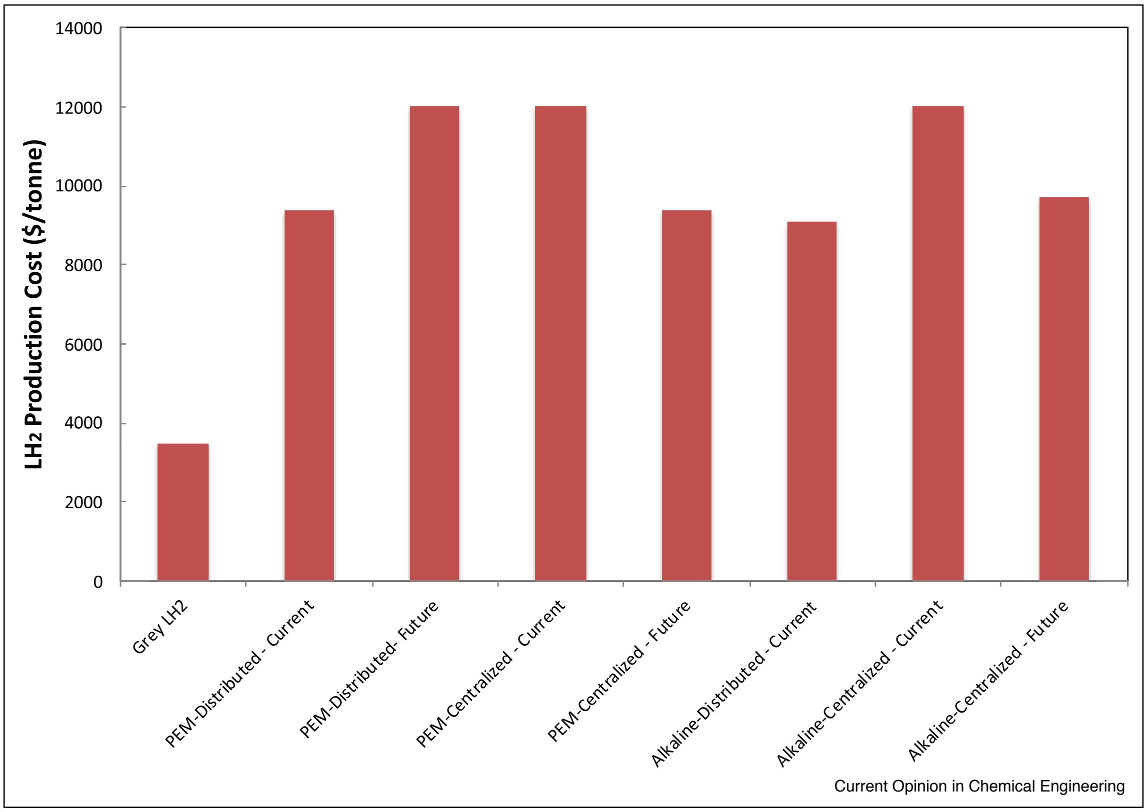


Greenhouse gas emissions data comparison (g CO_2e/MJ fuel) for LH_2 to grey, blue and green H_2 production [25,29,30,34].

example, the chemical looping reforming (CLR) option has a relatively low life cycle GWP and low fossil fuel consumption [23,24]. Nonetheless, introducing the carbon capture and liquefaction process units increase the cost of the SMR and ATR processes by 18 and 2%, respectively [25]. There are still some barriers to scale-up and commercialization of CLR technology. Heat integration of these complex gas-solid fluidized bed/moving bed reactors, as well as durability and attrition resistance of the metal oxide catalyst, is some technical uncertainties that might affect the energy efficiency and cost competitiveness of a large-scale plant [25,26]. Although hydrogen has virtually no tank-to-propeller (TtP) carbon footprint, its tank-to-propeller footprint can be high. As shown by Figure 2, the well-to-tank (WtT) carbon footprint of grey LH_2 ranges between 120 and 155 gCO_{2eq}/MJ energy contained in fuel. This number is substantial given that the well-to-propeller (WtP) carbon footprint of heavy fuel oil is about 90 gCO_{2eq}/MJ energy contained in the fuel [27,28]. Blue LH_2 has a lower carbon footprint which ranges from 40 to 90 gCO_{2eq}/MJ energy contained in fuel depending on the composition of the source of sequestered CO_2, the capture technology, and the utilization extent and route.

When green LH_2 is produced from renewable feedstocks and energy, the GHG emissions are significantly reduced but the cost and complexity increase. For instance, reported studies on the use of wind energy based on various locations (onshore or offshore) show that another layer of complication is added. Typically, the utilization of wind at the offshore energy harvesting turbine farms works with higher efficiency and lower GHG emissions. Liquefaction using renewables shows reduced levels of GHG emissions (4.6, 11.7, and 43.3 g CO_{2eq}/MJ fuel from wind, solar, and grid respectively) [29,30]. It is worth noting that liquefying hydrogen consumes about 30% of the energy content of hydrogen [31]. Furthermore, it is difficult to keep LH_2 at a low temperature (−253°C under 1 bar) and even with good insulation, evaporation and leakage will occur (typical estimates in the order of 1% of the stored volume per day) [32,33].

Figure 3



Comparison of LH_2 production costs via current and future technologies.

When the production costs are considered for LH_2 production via emerging routes, alkaline water electrolyzers have lower current and power densities but have lower initial cost (per kW basis). The only possible side-product for proton-exchange membranes (PEM) is H_2O, whereas, for Alkaline electrolyzer, possible side-products of significant risk in product hydrogen stream include: KOH, O_2, and H_2O. PEM electrolyzer does not need for a backup power supply to safely shutdown but an Alkaline electrolyzer also requires backup power system to safely shut down. H_2 production and liquefaction costs for green H_2 are very expensive because of the renewable electricity production cost. As the renewable energy cost gets lower, so will the cost of producing cleaner LH_2 production cost will get down. Figure 3 shows key data for production cost for current and future systems (with the future estimates based on predictions for the enhancement of performance).

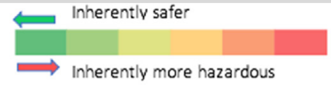
Furthermore, there are few issues regarding the utilization of LH_2 in bulk scales in the shipping industry through conventional internal combustion engines. One of the main issues related to the retrofitting of existing engine infrastructure is the engine knocking related to air–fuel ratio and intake temperature and the injection/ignition steps in the engine. The LH_2 ignition methods in internal combustion engines are considered to be dual-fuel operation with pilot diesel direct ignition or auto-ignition in the homogeneous charge compression ignition mode. In addition to conventional power units, alternator-based electric generating power units are being considered as drive modules of the ships, however, this method is still in its early stages.

Overview of hydrogen properties related to health and safety

Understanding the inherent hazards of hydrogen are essential before widespread use for global maritime transportation. Several factors should be assessed. The US National Fire Protection Association (NFPA) provides a standard system for hazard identification of materials for emergency response referred to as NFPA 704 [35]. The degree of hazard is ranked in increasing severity from category 0–4. Table 1 briefly compares the hazards of hydrogen to other representative energy sources based on the four NFPA 704 standards: health, flammability, instability, and special hazards. From the perspective of health and instability, liquid hydrogen (LH_2) is inherently the safer relative to other fuels with a rating of 0 in both these categories. Meanwhile, hydrogen has a high flammability

Table 1

Comparison of fuel hazardous characteristics via the US National Fire Protection Association (NFPA) 704



Hazard / Safety Category	FUELS							
	LH2	HFO/MGO[1,2]	Biodiesel	LPG	LNG	MeOH	EtOH	Ammonia
US NFPA 704								
Health	0	1	1	2	3	1	2	3
Flammability	4	2	1	4	4	3	3	1
Instability	0	0	0	0	0	0	0	0
Special	Asphyxiant gas			Asphyxiant gas	Asphyxiant gas			

HFO: Heavy Fuel Oil, MGO: Marine Gas Oil, MeOH: Methanol, EtOH: Ethanol.

risk according to the NFPA 704 standard that determines flammability categories based on flashpoints and boiling points. Although it is nontoxic, special handling is required for hydrogen or liquid hydrogen because it is an asphyxiant gas which can lead to suffocation through the dilution of the concentration of oxygen in the air.

As an extension of NFPA 704, Table 2 explores more detailed flammability aspects of hydrogen along with other fuels especially for the prediction of possible accidental explosion and/or fire incidents. Hydrogen is expected to be inherently more hazardous due to its high energy intensity as indicated by the lower heating value (LHV) of 120 MJ/kg (which is 2.8 times the LHV of Heavy Fuel Oil) [31], the wide flammable limit range, lower boiling temperature, and lower flash temperature. Nonetheless, other chemical properties, such as higher auto-ignition temperature and lower vapor density, indicate that hydrogen is inherently safer than other fuels. Consequently, chemical incidents occur due to a wide variety and combination of factors making the overarching comprehension of various hazard aspects of hydrogen is crucial to handling the fuel safely and effectively.

Table 3 shows the key properties for alternate shipping fuels. Numbers in Table 3 related to LH_2 provides insights on the bunkering related challenges as it requires cryogenic conditions for bulk storage as the liquefaction temperature of LH_2 is $-253°C$ at 1.013 bar with a low density of 71 kg/m^3. Considering the physical conditions of LH_2, the amount of bunker fuel will depend mainly on the ship's sailing time and engines-specific fuel consumption. Some other considerations must be taken into account in estimating the amount of fuel to be stored onboard such as the expected amount of boil-off LH_2 due to the heat transfer through the bunker. The lower heating value (LHV) per kg and the volumetric energy density, respectively impact the weight and volume of the fuel to be stored on the ship. For instance, compared to LNG, LH_2 carries 2.4 times the energy of the same mass of LNG but requires 2.8 times the volume to store. The low temperature for storing LH_2 under atmospheric pressure ($-253°C$) poses several hazards. It can cause cold burns upon exposure. Additionally, upon leakage, it can create a mixture of liquefied air and hydrogen which can lead to an explosive mixture or the creation of flammable/explosive pathways [39•,41]. Therefore, in order to select alternative fuel, the implications for logistics, infrastructure, and safety need to be considered. Considering both small-scale and large-scale storage alternatives, refueling time needs to be addressed and improved. On the other hand, the durability of the storage vessels/bunkers as well as the codes and standards of hydrogen bunkering and onboard storage systems needs to be well defined in order to facilitate implementation/commercialization and ensure safety and public acceptance. Furthermore, detailed full-scale life cycle and efficiency analyses on cost and efficiency for hydrogen storage systems need to be carried out [23]. Because of the need to build an infrastructure and to gain operational experience, hydrogen fuel can initially be tested mainly by smaller vessels operating on fixed routes, at which there will be limited infrastructure

Table 2

Comparison of the potential of explosion and fire [36–38]

Inherently safer
Inherently more hazardous

Hazard/Safety Category	FUELS							
	LH_2	HFO/MGO	Biodiesel	LPG	LNG	MeOH	EtOH	Ammonia
Criterion 1: Flammability limits- vapor-air mixtures will ignite and burn over a well-specified range for compositions. A wider range increases the limits in which a fire or explosion could commence.								
Lower heating value [MJ/kg]	120	42.7	37.4	46	50	19.9	26.7	18.6
Flammable limit range	71	9.7	-	7.5	9.7	29.3	15.7	13
Criterion 2: the potential of self-ignition In presence of oxygen all materials heated above their ignition temperature will burn								
Auto ignition point [C°]	520	250	220	470	540	464	363	650.9
Boiling point [C°]	-252.9	175	315	-42	-161.5	64.7	78	-33.3
Flash point [C°]	-259.2	61	100	-104	-175	12	17	-64.2
Criterion 3: Cloud formation and Flame propagation - 'vapor density' or 'diffusion coefficient' would be related to buoyancy (e.g., LH2 evaporates for a short period due to its high buoyancy)								
Vapor Density air=1	0.10	5	0.88	0.56	0.55	1.10	1.60	0.80

Table 3

Comparison of different marine fuels [37,40]

Fuel type	LHV [MJ/kg]	Volumetric energy density [GJ/m^3]	Storage pressure [bar]	Storage temperature [°C]
Liquid H_2	120	8.5	1	−253
Compressed H_2	120	2.7	350	25
Compressed H_2	120	4.7	700	25
Liquid NH_3	18.6	12.7	1/10	−34/20
MeOH	19.9	15.8	1	20
LNG	50	23.4	1	−162
MGO	42.7	36.6	1	20

requirements (e.g. bunkering and onboard storage). Gradual implementation of hydrogen fuel on the busiest maritime lines can be implemented as the engine technology is fully developed which is anticipated by Q4/24. The main challenge on that is the requirement of the extra space needed by hydrogen, as it raises concerns in the industry as there might be a reduction in the existing cargo space in order to make room for the fuel. However, according to the International Council on Clean Transportation (ICCT), this barrier could be overcome. It's been found that 43% of current voyages between China and the United States could be made using hydrogen without the need for extra cargo space or to stop more than usual times to refuel [42]. Eventually, it is estimated to be near all the voyages could be powered by hydrogen with only minor changes to fuel capacity.

Conclusions

Conventional routes for the production of grey hydrogen are economically competitive with a vast infrastructure and almost no TtP carbon footprint. Nonetheless, when the whole LCA is considered by incorporating WtT steps, the carbon footprint of grey LH_2 is substantial (120–155 gCO_{2eq}/MJ contained energy). This number is substantial given that the WtP carbon footprint of heavy fuel oil is about 90 gCO_{2eq}/MJ energy contained in fuel [27,28]. Blue LH_2 has a lower carbon footprint which ranges from 40 to 90 gCO_{2eq}/MJ energy contained in fuel depending on the composition of the source of sequestered CO_2, the capture technology, and the utilization extent and route. Green LH_2 shows reduced levels of GHG emissions (4.6, 11.7, and 43.3 g CO_2e/MJ fuel from wind, solar, and grid respectively). In considering safety and health issues, there are advantages and disadvantages for using LH_2. It is nontoxic but can lead to asphyxiation. The high energy density of LH_2 (2.8 times that of HFO on an MJ/kg basis) is advantageous from a shipping perspective but when coupled with the wide flammable limit range, lower boiling temperature, and lower flash temperature, it can pose higher fire and explosion risk. On the other hand, LH_2 has advantageous chemical properties that can lower the fire and explosion risk, such as higher auto-ignition temperature and lower vapor density.

Green LH_2 is among the few promising options to meet the IMO's goals of reducing carbon emissions by at least 40% by 2030 and by 70% by 2050 relative to the 2008 emissions. At present, the production cost of green LH_2 is 3–4 times that of grey LH_2. The maritime industry accounts for ~2.2% of global CO_2 emissions [43]. It has been forecasted that the implementation of an additional 5% hydrogen-fired power generation could lead to global emissions reductions up to 9% [44].

Most of the considered hydrogen supply chain pathways would release significantly less CO_2 in comparison to conventional fuels and their corresponding utilizations in the maritime industry. The supply chain of the hydrogen fuel economy is mostly dependent on the type of the hydrogen production route. The main issues to consider in supply chain-related issues are bulk shipping and the utilization demand [45]. There is a certain need for improvement or modernization of the cargo containment systems to serve extreme cryogenics as well as minimization of the boil-off product loss via LH_2 propulsion. Furthermore, safe operation of loading-transit-offloading routines and establishing globally accepted the liquefied hydrogen standards and regulation is one of the biggest challenges on the global supply chain of the liquefied hydrogen fuel. However, above all, the creation of global utilization and demand for hydrogen fuel is a must on the supply chain development in order to reach the ambitious targets on the CO_2 reduction in the maritime industry. As technological advances are made in renewable energy harvesting and hydrogen production, these costs are expected to drop. More research is also needed to create novel materials for safe and efficient storage of hydrogen for on-board storage as well as bunkering purposes.

Conflict of interest statement

Nothing declared.

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- of special interest

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