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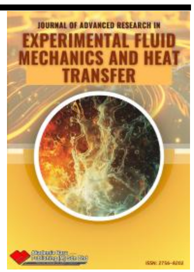

Hydrogen Application as a Renewable Fuel in the Internal Combustion Engine and Fuel Cell towards Zero Carbon Emission: A Technical Review

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ABSTRACT

Global efforts to lessen environmental effects, particularly in the marine industry, which make up around 90% of global trade, are led by the switch from traditional fossil fuels to renewable energy. Carbon emissions from cargo ships, including tankers, container ships, and bulk carriers, have become a significant concern due to the rising need for marine transportation. With a primary focuses on shipboard applications, this study compares internal combustion engines with fuel cell technology to assess hydrogen as a potential alternative fuel for the marine industry. One benefit of using hydrogen as a combined fuel with other fuels is that it can cut greenhouse gas emissions by as much as 40%. Fuel cell technology is more efficient than hydrogen-fuelled ICEs, reaching up to 60%, while internal combustion only reaches 20-25%. In addition, fuel cells produce no carbon emissions, making them more environmentally friendly. However, significant challenges include the cost of hydrogen production, limited storage and distribution infrastructure. The study also discusses technical and operational aspects, including hydrogen storage methods, such as compressed storage, cryogenic storage, and electrochemical storage, and emissions challenges faced by hydrogen-fuelled ICEs, such as increased NOx emissions due to high combustion temperatures. The analysis concluded that hydrogen fuel has great potential to support the decarbonization of the maritime sector. This review paper offers an extensive examination of the opportunities and obstacles linked to the utilization of hydrogen as a renewable fuel, specifically in the context of fuel cell engines, and internal combustion, and establishes a basis for promoting sustainable renewable energy within the maritime sector.

1. Introduction

Energy shift from conventional to more environmentally friendly energy is needed, especially in the maritime industry. Roughly 90% of world trade is transported by ships, which commands about 70% of the entire value of international trade; thus, the marine sector has become one of the major drivers of global commerce [1]. According to Figure 1, cargo ships are typically a significant source of pollution worldwide. Worldwide cargo ships are divided into dry carriers, containers, and tankers.

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These three types exhibit different variations of stability modes [2]. These vessels conduct shipping and intercontinental trade, without which intercontinental shipping and trade and bulk transportation of raw materials and manufactured goods would not be possible [3]. Also described in Figure 1, some types of cargo ships will experience an increase in demand for cargo ships, which is expected to increase by 60% by 2050 [3]. This demonstrates the importance of more environmentally friendly fuels for the maritime sector to meet future demand and reduce exhaust emissions [4].

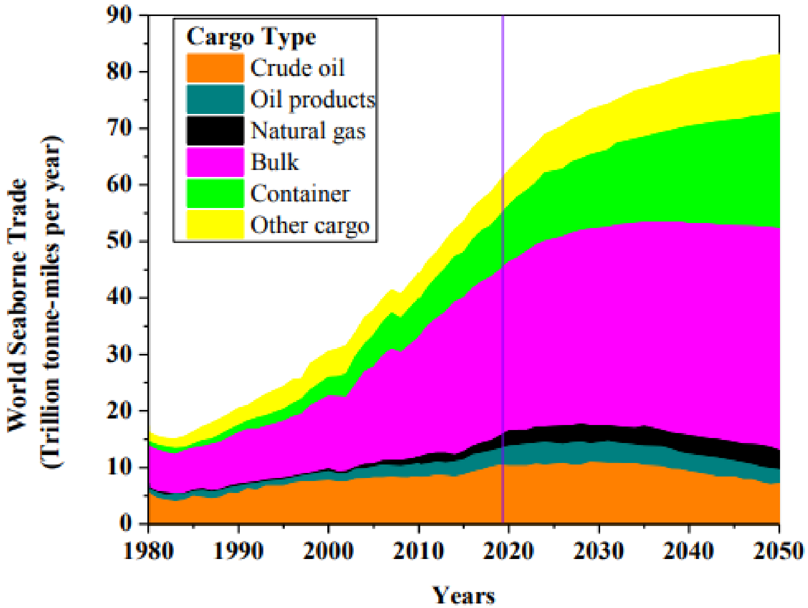


Fig. 1. Increased demand for marine transportation modes [9]

Reducing these exhaust emissions aligns with the International Maritime Organisation (IMO) targets described in Table 1, which aim to reach zero emissions by 2050 [5]. The maritime sector is paramount to the global economy, as maritime transport, such as ships, transports most goods to be traded. Despite its role in international trade, the industry also faces significant challenges related to environmental and security impacts. Based on the data from October 2023, crude oil, natural gas, and coal form the three primary sources of energy production [6]. Heat or electricity is needed from the primary energy sources, which are conventionally and renewably generated, resulting in energy losses [7]. Decreased investment in conventional fuel sources would make hydrogen a competitive global energy source [8].

Table 1
IMO target for reducing emission [5]

Year	Target
2030	Reduce gas emissions by at least 20%, up to 30%
2040	Reduce gas emissions by at least 70%, up to 80%
2050	Achieving the net-zero emission target

Several alternative marine fuels are being researched and evaluated to reduce emissions, especially carbon from the maritime sector. The evaluation and research aim to minimize the environmental impact of over-gassing marine transport and meet increasingly stringent emission regulations. The fuels of most interest and research are hydrogen (H_2), ammonia, liquefied natural gas, biodiesel, methanol, ethanol, and biogas. Ammonia – H_2 is considered a popular alternative fuel being used and researched today, as it is thought to reduce the impact of global warming significantly [10]. When used as a dual fuel with conventional fuel oil, the presence of hydrogen reduces greenhouse gas emissions by 40% and the presence of ammonia by 27% [7]. Figure 2 shows the energy storage and distribution for internal combustion engines and fuel cells.

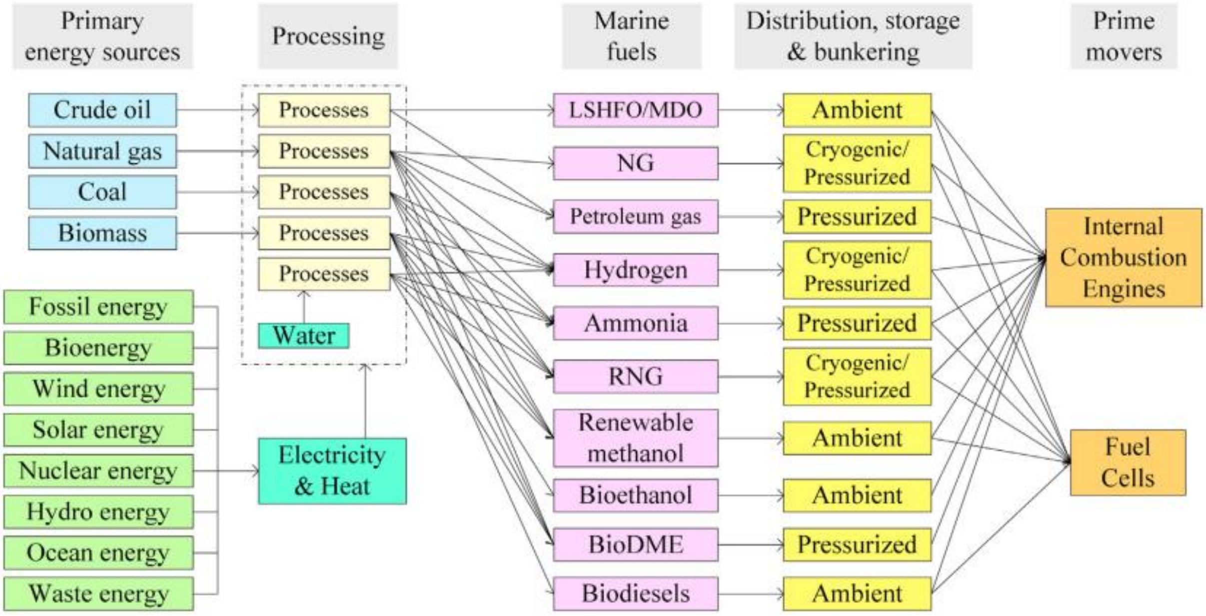


Fig. 2. Energy storage and distribution for internal combustion engines and fuel cells [11]

However, the application of hydrogen - ammonia faces significant challenges, such as production costs and inadequate infrastructure are taken from the previous study [12,13]. Biodiesel and biogas are also renewable fuels that can reduce dependence on conventional fuels (petroleum-based fuels). Biodiesel might increase specific fuel consumption and nitrogen oxide (NOx) emissions, although it decreases other harmful pollutants, biogas is now considered an efficient and sustainable fuel for short-, medium-, or long-term use [14].

Applying technology, two different technologies convert chemical energy into usable energy but with other mechanisms and efficiencies. Fuel cell technology is a technology that utilizes the electrochemical reaction between H_2 and oxygen (O_2) to generate electricity; this technology produces water as the only emission [14]. Fuel cells themselves have very high efficiency compared to internal fuel engines, reaching 60% efficiency [15]. In addition, this technology also has a lower environmental impact because it does not produce carbon emissions [16,17]. One technology, in addition to fuel cells, to reduce engine emissions is to modify the internal combustion system (ICE) by using hydrogen in combination (H_2 - ICE) to achieve 20-25% efficiency and produce lower emissions than fossil fuels, although still lower than the technologies described in the previous paragraph [18].

Despite their advantages, alternative fuels in the maritime sector also pose challenges, mainly regarding infrastructure production costs and ship engine technology adaptation [12]. In addition, government policies and initiatives are needed to encourage the introduction of renewable marine fuels [12]. Therefore, this paper presents an in-depth study of hydrogen fuel. It will also discuss why hydrogen is an alternative fuel and include in-depth research on fuel cells and combustion engines.

The studies dealing with hydrogen as fuel and its use for motive power purposes on board ships during the present research were identified by literature searches using comprehensive terms covering a broad field, from fuel cell technologies in internal combustion for maritime applications to hydrogen fuels. The results of this search are summarised in Table 2, which provides the entire search query along with the number of documents found.

Table 2
Full search queries and the corresponding number of records

No	Query	Records found
1	Hydrogen fuel OR alternative marine fuels AND decarbonization	3,314
2	Hydrogen fuel AND marine propulsion	3,109
3	Hydrogen fuel AND Marine Propulsion AND Fuel Cells	2,301
4	Hydrogen fuel AND Marine Propulsion AND Combustion Engines	1,936
5	Fuel Cells for Marine Applications OR Combustion Engines for Marine Applications	36

The following research is a compilation of the most cited and referenced papers in studies related to alternative fuels, fuel cell technology, and emission reduction strategies. Of those, the review of PEM fuel cell materials, technology status, and fundamentals by Wang *et al.,* [19] is leading with 821 citations, followed by studies on methanol as an internal combustion engine fuel by Verhelst *et al.,* [20] and ammonia for compression ignition (CI) engines by Dimitriou and Javaid [21]. This paper highlights the advancement of fuel cell technology in several applications, with a particular focus on hydrogen as a renewable fuel type. The study seeks to analyze hydrogen in-depth as a stand-alone option for the further development of renewable fuels and its use in fuel cell technology and internal combustion engine technology.

The transition to hydrogen as a sustainable fuel for ships is widely dealt with by researchers, who have investigated its various areas including production, storage and application for shipping. Various past studies have examined hydrogen and its potential use in internal combustion engines (ICE) and fuel cell (FC) systems; it has treated these two configurations separately, focusing on their benefits and drawbacks. What is still lacking is an in-depth study that compares these two technologies based on efficiency, emissions and economic feasibility with respect to their applicability to the maritime sector. The absence of such a comparative study precludes the taking of holistic cognizance of the more viable technology for large-scale adoption on ships. Besides acknowledging some of the challenges that come with the application of hydrogen, such as its high production costs, limitations in storage and government regulations, the current discussions fail to compile information on how these barriers can be overcome. Thus, this paper intends to fill that gap by providing a comprehensive performance comparison between hydrogen-powered ICEs and fuel cells, and also evaluate their technical and economic feasibility and address some of the major challenges of hydrogen adoption in the marine industry.

2. Hydrogen Production Methods

2.1 Steam Methane Reforming

Historically a mature and widely applied hydrogen-generating technology, the steam methane reforming process involves the reaction of natural gas and steam at elevated temperature to give hydrogen and carbon dioxide. With a formidable efficiency and economic advantage, steam methane reforming is the main process for large-scale hydrogen production [22]. The reaction is generally carried out in two steps: first, the reforming reaction, followed by the water-gas shift reaction for converting carbon monoxide into carbon dioxide and producing more hydrogen. The method is very efficient, but it has huge carbon dioxide emissions, which renders it less sustainable than other modes of hydrogen production. Against these emissions, the integration of the steam methane reforming process with carbon capture and storage technologies can be employed to capture carbon dioxide produced during production and store it deep underground to prevent its return to the atmosphere.

2.2 Electrolysis

Electrolysis of water is a promising future method for hydrogen generation from renewable energy sources because it constitutes a sustainable alternative to tradition fossil fuel-based methods, including that highlighted by Wilkinson *et al.,* [23]. This process involves electricity usage to dissociate water into hydrogen and oxygen, while avoiding any direct release of greenhouse gases. There are different electrolysis types such as alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis, having various relative merits and demerits. Alkaline electrolysis is the most mature and widely used technology. Proton exchange membrane electrolysis has higher efficiency and enables higher pressures, whereas solid oxide electrolysis is currently under development but has the potential for very high efficiencies at high temperatures. Water electrolysis has started to demonstrate progress towards scalability to relevant capacities to meet the need, but material and manufacturing advances must be realized to meet the cost targets [24].

Electrocatalysts are responsible for enhancing the efficiency of water electrolysis processes and reducing the costs associated with these processes. Efficient electrocatalysts based on platinum group metals with high intrinsic activity have been reported, but these metals are very expensive and are highly scarce, resulting an increased catalyst cost thataccounts for approximately 8 percent of the stack cost of electrolyzers [25]. Development of cheap but efficient catalysts for splitting water is of prime importance. Water electrolysis is envisaged to become the dominant method of hydrogen production in industries to realize an economy for sustainable and green hydrogen. It will be especially applicable when its power supply is sourced from renewable energies like sunlight or wind and the low-grade water or seawater resource is used [25].

2.3 Biomass Gasification

Biomass gasification is a process whereby biomass is transformed to a gaseous mixture that is primarily composed of hydrogen, carbon monoxide, and methane. This conversion is achieved by heating biomass in a low oxygen environment. Once produced, the gas mixture can be further processed to separate the hydrogen from other gases. Biomass gasification is a renewable route to hydrogen generation from various forms of biomass, such as wood, agricultural residue, or energy crops. Coupling electrolysis with renewable energy, such as solar or wind power, would create a truly renewable hydrogen economy [26,27]. However, efficiency and economic feasibility within biomass gasification generally depend on the biomass type and its quality of feedstock, as well as the design and operation of the biomass gasification system.

2.4 Photobical Hydrogen Production

Photobiological hydrogen production is production of hydrogen with the use of biological agents that are microorganisms, algae and bacteria using sunlight and water. This hydrogen production is similar to photosynthesis where green plants use sunlight to transform water and carbon dioxide into energy. Photobiological hydrogen production could be a sustainable and eco-friendly technology for hydrogen production using renewable resources and reducing greenhouse gas emissions. Currently photobiological hydrogen production system has low efficiency and a lot of research is needed to improve this biological systems performance [28]. Fast pyrolysis followed by steam reforming of bio-oil, supercritical water gasification, steam gasification, and other modern thermochemical methods are promising [29]. Slow pyrolysis-steam gasification also gives higher yield and quality of hydrogen [29]. An effort to combine slow pyrolysis and steam gasification is being investigated for improving hydrogen yield and quality [29]. Various photobioreactor systems have been tested in lab-scale hydrogen production experiments, with some projects aiming to scale up the process [30].

Table 3 shows comparison of hydrogen production. However, hydrogen production is a very critical barrier because it is mostly produced by thermochemical methods [31]. Electrolysis using renewable or nuclear power brings down the greenhouse gas emissions and leaves a more environmentally sound alternative [31]. The versatility of hydrogen enables it to serve various sectors: transportation, energy storage, industry, medicine, and power-to-gas systems, where it serves as a substitute for conventional fuels in a way that is environmentally and health conscious. Hydrogen technologies are necessary to achieve environmental and energy goals. The three major avenues for producing hydrogen are steam methane reforming, electrolysis, and biological sources [32].

Table 3
Comparison of production methods

Method	Description	Efficiency	Impact	Challanges
Steam methane reforming (SMR)	Reacts methane with steam at high temperatures to produce hydrogen and CO_2	60-75%	High CO_2 emissions, requires CCS for low-carbon production	Dependence on fossil fuels, carbon emissions
Electrolysis	Uses electricity to split water into hydrogen and oxygen	70-85%	Zero emissions if powered by renewables	High electricity cost, infrastructure limitations
Biomass gasification	Converts biomass into syngas containing hydrogen	30-50%	Lower emissions than SMR, depends on sustainable biomass	Feedstock availability, lower efficiency
Photobiological hydrogen production	Uses microorganisms like algae to produce hydrogen via photosynthesis	~10% (low)	Environmentally friendly	Low efficiency, scalability issues

3. Hydrogen Storage Methods

Hydrogen storage methods are an essential aspect to consider in supporting hydrogen as a sustainable energy source. Efficient, safe, and economical hydrogen storage is necessary to ensure its availability in several applications, from transport to power generation. The following flowchart summarises the three main methods of hydrogen storage based on their characteristics and operating conditions.

Figure 3 is a flow chart explaining hydrogen storage methods based on references from several studies. Hydrogen storage methods are grouped into three main categories: (i) Compressed or gaseous storage, which involves storing hydrogen in gaseous form at high pressure, usually between 350 and 700 bar [33]. This technology is widely used because the supporting infrastructure is widely available. However, this method requires robust and pressure-resistant tanks to ensure safety. (ii) Cryogenic storage, also known as liquid storage, is the storage of hydrogen by keeping it in liquid form at very low temperatures, around 20.28 K or -252.87 °C [34]. The gained advantages of storage of large volumes of hydrogen in small volumes are offset by the primary constraints, which are high costs associated with low-temperature maintenance and loss of hydrogen by evaporation (boil-off) [35]. (iii) electrochemical or solid storage involves storing hydrogen in solid chemical compounds inside porous materials, such as metal hydrides or carbon nanostructures [36]. This method is attractive due to its high safety potential and good storage density. However, the efficiency of hydrogen release from the storage material remains a challenge. These three methods have advantages and disadvantages, which are tailored to specific needs, such as application, cost, and energy efficiency.

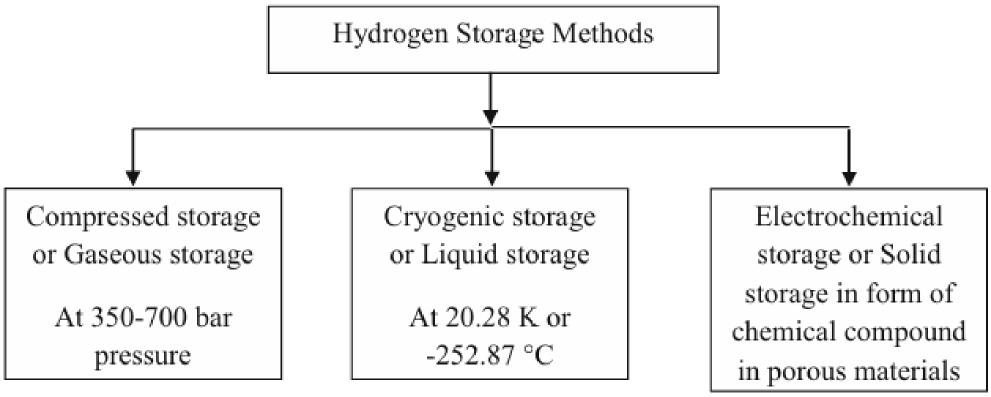


Fig. 3. Flow chart storage methods [37]

One of the challenges that still remains with regard to hydrogen release from the storage medium is efficiency. A comparative study on the other hand, with research into hydrogen alongside other alternative fuels, throws light on the disadvantages and advantages in terms of storage and utilization. While Table 4 concerning properties of hydrogen, ammonia, LNG, and marine gas oil provides density, heating value, boiling point, and flammability limits, it is not only about these properties. Some of these features are significant in determining the feasibility for hydrogen storage and use in the maritime sector. Properties Comparison and Alternative Fuels is a table that examines the most important characteristics of alternative fuels effective in maritime operations. The table gives such properties as density (kg/m³), lower heating value (MJ/kg), boiling point (°C), auto-ignition temperature (°C), flash point (°C), liquid energy density (MJ/L), and upper and lower flammability limits (%v/V). Such knowledge is needful because it helps determine how well and how safely alternative fuels may be used in maritime procurements and ultimately helps select the best fuel for reducing emissions and improving energy efficiencies in the industry and work sectors. All the developments above in hydrogen have been possible due to its very high inherent capabilities as a fuel. This element is more likely to clean the environment because fewer greenhouse gases and poisonous emissions from ships that burn fossil fuels will be released into the atmosphere.

Table 4
Properties comparation and alternative fuels [38]

Properties	Marine gas oil (MGO)	Methane (LNG)	Ammonia	Hydrogen
Density (kg/m^3)	900	430	696	7.8
Lower heating value (MJ/kg)	42.7	48	22.5	120.2
Boiling point (°C)	180-360	-161	-33	-253
Auto-ignition temperature (°C)	250	537	630	585
Flashpoint (°C)	Greater than 60	-199	132	-
Liquid energy density (MJ/L)	38.4	20.6	15.7	8.51
Upper flammability unit (%v/V)	5	17	25	75
Lower flammability unit (%v/V)	0.7	5.3	15	4

4. Fuel Cell Technology for Marine Applications

The research relates to the work done by *Menon and Chan*, [39] in investigating a hybrid energy system implemented on a vessel, as shown in Figure 4. The system has different components: batteries, proton exchange membrane fuel cells, motor generators, and liquid hydrogen tanks. In this case, the liquid hydrogen tank represents the primary storage of hydrogen, which is afterward transformed into electrical energy using the PEMFC. The electrical power is distributed via a 750 VDC switchboard to support direct current architectures. Figure 5 shows the basic schematic diagram of hydrogen fuel cell.

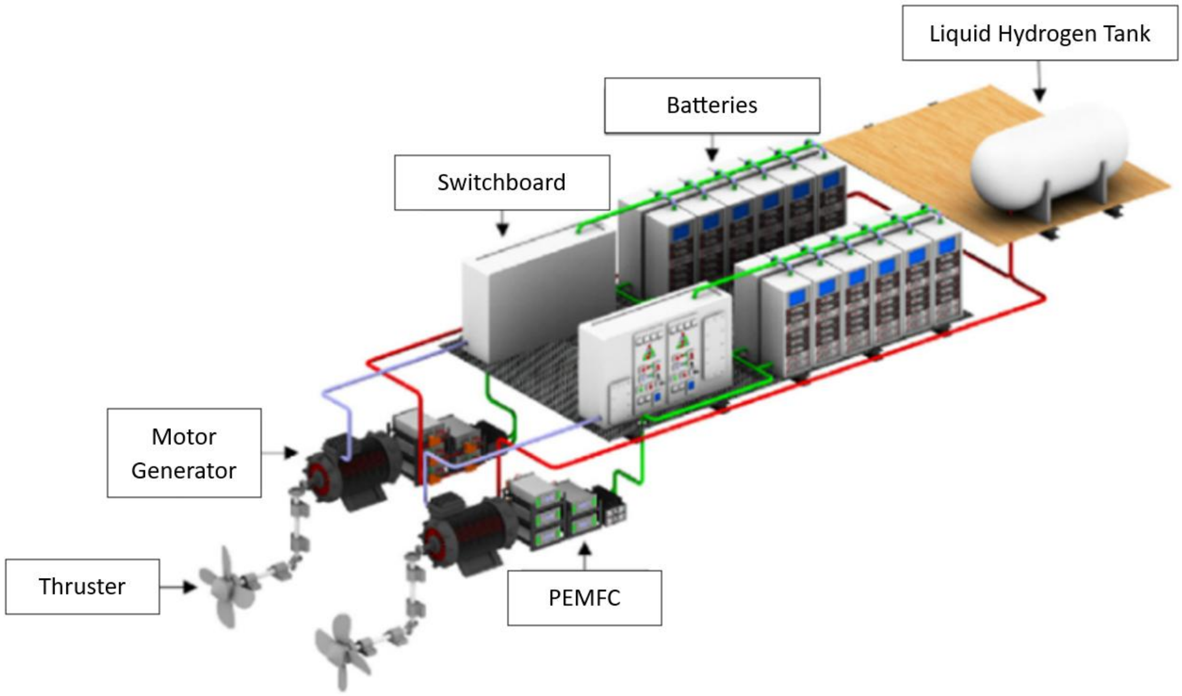


Fig. 4. Fuel cell technology system [39]

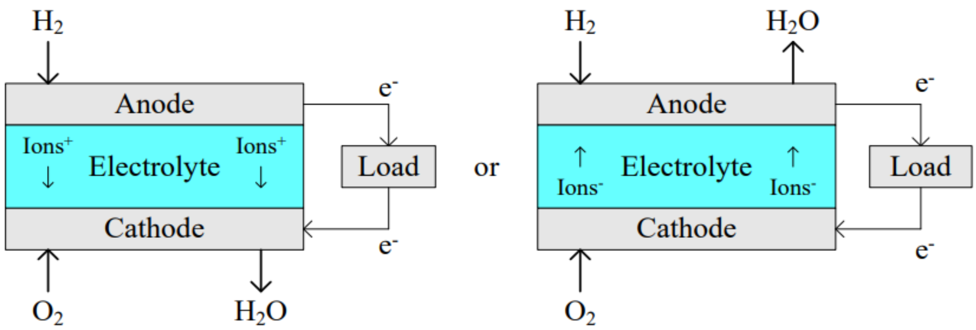


Fig. 5. Hydrogen fuel cell basic schematic [40]

This architecture supports system integration while reducing the need for direct current to alternating current conversion. In addition, the battery is an energy storage mechanism that can store the energy generated by the motor generator under the Power Take-Off (PTO) mode and, in return, provide extra power under the Power Take-In (PTI) mode. The generator motor converts electrical energy into mechanical power to drive the thruster to provide the thrust necessary for ship movement. The entire system is designed to easily and quickly respond to transient load changes that a vessel faces during berthing or towing by using energy flow under the control of an efficient electrical circuitry [41]. The design allows the use of clean fuels, better management of energy, and longer equipment life.

4.1 Hydrogen Supply Method – Fuel Cell

The workings of hydrogen engines, especially for a single fuel cell system, can be elaborated by the explanation presented below and in Figure 6. First, hydrogen is pumped into the cell and then passes through the flow plate. Then, at the anode, a point in devices where electrons flow out at the next point, hydrogen will undergo molecular breakdown. Using a platinum catalyst introducer, the hydrogen molecule must be separated into positively charged hydrogen ions and negatively charged electrons. Third, positive hydrogen ions are then allowed to pass through a polymer membrane, known as a polymer electrolyte membrane (PEM); in this case, only the positive ions can pass through the polymer membrane.

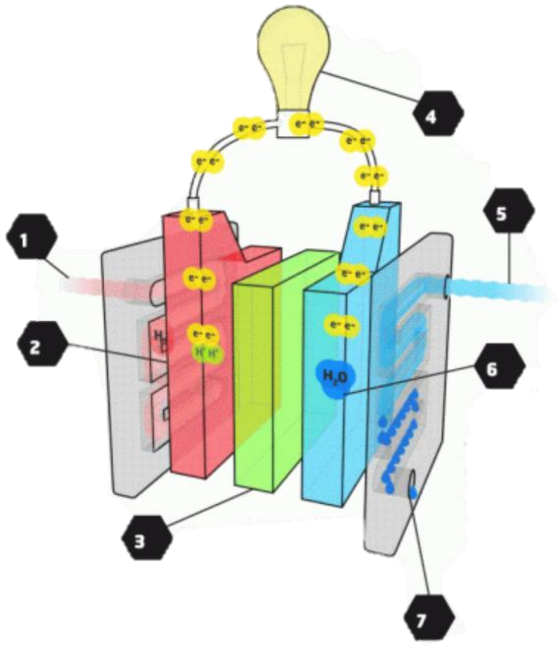


Fig. 6. Fuel cell system [42]

However, the negative ions are forced to remain in an external circuit, creating an electric current flow - like water flow that could drive a waterwheel. Based on the visualization created in the fourth stage, these separated the electron flows over the external circuit, creating an electric current. At the same time, as seen in point 5, oxygen is pumped through the flow plate into the cell. In stages six and seven, the cathode is another catalyst that allows negatively charged electrons, positively charged hydrogen ions, and oxygen to combine into water-H_2O. The formed water is then taken out of the cell. The whole process illustrates the working cycle of the hydrogen engine in generating electricity.

4.2 Fuel Cells based on Types, Pros and Cons

The type of fuel cell used depends mainly on its operating conditions, performance characteristics, and specific application [43]. Each type differs in the electrolyte material used, which is important in determining functionality and efficiency. Different categories of fuel cells have particular characteristics defined by the membrane utilized in its fabrication. Yttria-stabilized zirconia membranes in a Solid Oxide Fuel Cell (SOFC) allow for the conduction of oxygen ions at high temperatures; therefore, such cells work best in high-efficiency requirements for an application [44]. In contrast, a Direct Methanol Fuel Cell (DMFC) and a Proton Exchange Membrane Fuel Cell (PEMFC) both use a Nafion-based solid polymer electrolyte, acting as a conductor for protons in electrochemical processes, with a key differentiation in terms of fuel types utilized [45].

On the other hand, a Phosphoric Acid Fuel Cell (PAFC) utilizes a Phosphoric Acid (H_3PO_4) as its electrolyte, allowing for ion conduction at intermediate temperatures; this technology was one of the first to be commercialized [46]. On a different note, an Alkaline Fuel Cell (AFC) utilizes a Potassium Hydroxide (KOH) solution as its electrolyte medium for ion conduction in a fuel cell reaction [46]. All types of fuel cells have specific strengths and can be utilized for a particular application according to membrane types and desired energy requirements.

The only thing that differentiates the fuel cell technology is the membrane-in. Figure 7 shows how a fuel cell technology that derives power from an electrochemical reaction between oxygen and hydrogen works. There, hydrogen fuel (H_2) and oxygen ions (O^{2}-) from the electrolyte react at the anode to form water (H_2O), electrons (e-), and heat [67]. The electrons generated at the cathode from the reduction reaction will flow through an external circuit to the anode, generating an electric current that can be utilized to do practical work for electrical loads. Moving to the cathode, atmospheric oxygen takes electrons from the external circuit, giving rise to O^{2}-, which diffuses through electrolytes to the anode to continue the reaction. In the solid electrolyte layer of the MEM region, O^2 conduction takes place, creating a separation for the chemical reactions at the anode and cathode [68]. H_2O and heat are byproducts of the previously-mentioned reaction, while unreacted gas is vented from the anode side. Table 5 shows us an overview of the pros and cons fuel cells based on type. In contrast, the table below gives general data on the characters of each fuel cell type classified as SOFC, DMFC, PAFC, PEMFC, and AFC.

Table 5
Pros and cons of fuel cells based on type

Type	Pros	Cons
SOFC	i. High efficiency (45-65%) can reach up to 85% in combined heat and power applications [47]. ii. Can use several types of fuels, which includes hydrogen, methane, and natural gas [48].	i. Operation at such high temperatures (600-1200 °C) can cause material and wear problems [49]. ii. High initial cost for systems and components [50].
DMFC	i. Fast refilling with liquid methanol, easy to transport and store [51]. ii. Low emission only produces water as a by-product [52,53]. iii. Good energy density for portable applications [54].	i. Lower efficiency compared to SOFC and PAFC [55]. ii. Vulnerable to carbon dioxide which can interfere with the reaction [56].
PAFC	i. Good stability and long life in stationary operation [57]. ii. Better tolerance to carbon monoxide (CO) than other types [58]. iii. Suitable for large-scale power plant applications.	i. High cost of platinum catalyst. ii. Lower efficiency than SOFC (about 40-50%) [59].
PEMFC	i. Operation at low temperatures (60-80°C), enabling fast start-up [60]. ii. High efficiency and fast response to load changes [61]. iii. Wide application potential in transport and small power plants.	i. Requires pure hydrogen, which is difficult to produce and store [62]. ii. Membrane can be degraded by moisture and other contaminants [63].
AFC	i. High efficiency in energy conversion, especially with pure hydrogen [64]. ii. Lower operational costs compared to some other fuel cells [65]. iii. Better tolerance to carbon dioxide compared to PEMFC [58].	i. Carbon dioxide in the fuel can impair engine performance [58]. ii. Requires more frequent maintenance due to electrolyte degradation at high temperatures [66].

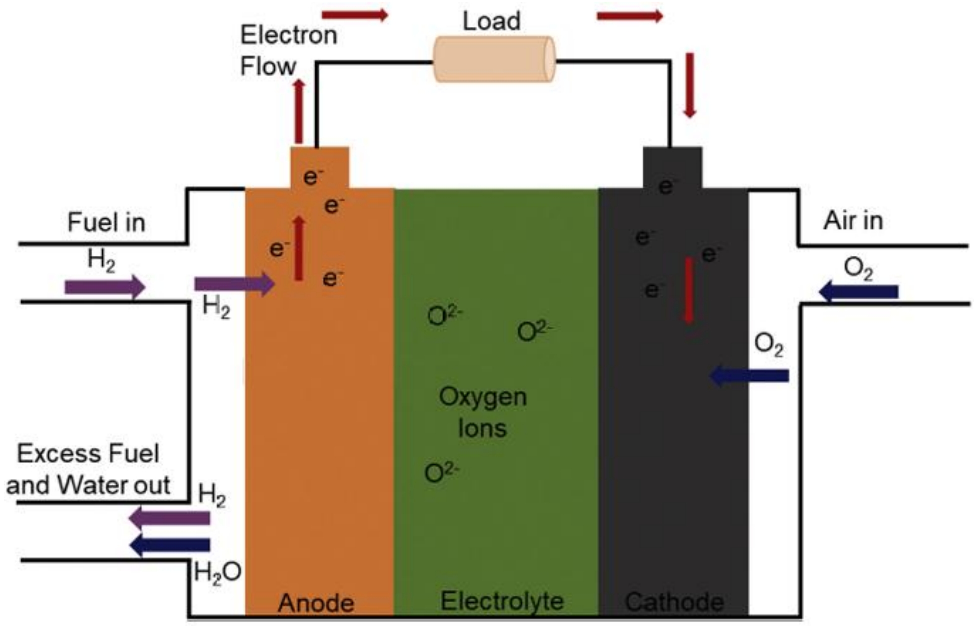


Fig. 7. Fuel cells workflow with hydrogen [44]

5. Hydrogen Combustion Engines

As shown in Figure 8, the internal combustion engine uses hydrogen fuel for energy, while the powertrain operation is the same as a conventional internal combustion engine [69]. ICEs inject hydrogen gas into a combustion chamber instead as a substitute traditional fuel to produce mechanical energy previously converted through heat energy, which will be used to move the piston [70]. This rotation drives the shaft, providing the necessary thrust for the azimuth pusher to transfer power to the auxiliary generator that supplies electricity to several loads, including lighting systems, motors, and pumps [39].

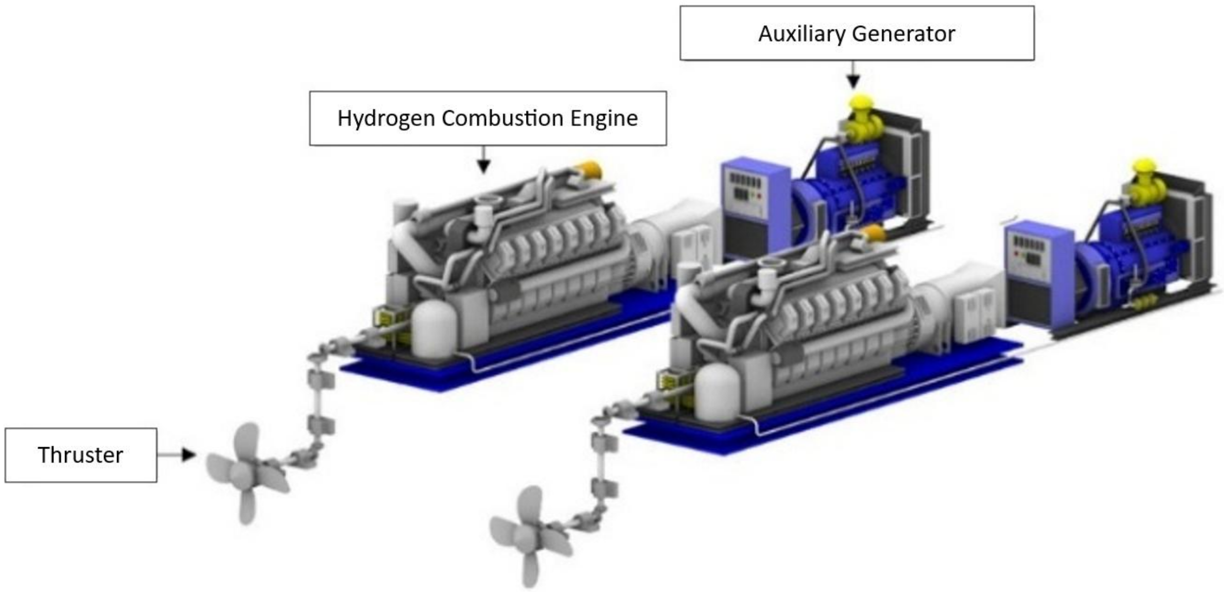


Fig. 8. ICE technology system [39]

5.1 Direct and Secondary Fuel Hydrogen

Conventional engines use liquid fuels, such as gasoline and diesel, but some motor cars run on natural gas [71]. Typical engines cannot use hydrogen fuel in its unaltered state without altering the combustion system. Hydrogen can act as a primary and secondary fuel in ICEs, but its use in a single-fuel capacity involves specific disadvantages. Thus, it is preferable to utilize hydrogen in a supplementary role [72]. While ICE technology will not eliminate dependence on fossil fuels, H_2 blending will save costs in terms of fuel and harmful emissions [72].

5.2 Combustion in ICE

In general, the structure of a hydrogen fuel engine is similar to that of a conventional engine [72]. To optimize hydrogen combustion, a ratio of 1:34 is necessary, wherein one component of H_2 must be combined with 34 parts of air in the cylinder [73]. In its utilization, three techniques of using hydrogen fuel were investigated to prevent the shortcomings of its potential as a fuel cell, which will be discussed in the next sub-point [74].

5.3 Evaluation of ICE Performance on Hydrogen Fuel

Hydrogen generally raises an engine's thermal efficiency, with its high octane rating and combustion rate contributing to this improvement. In addition, hydrogen combustion releases no carbon emissions, including CO and CO_2, and is a cleaner alternative to conventional fuels [75]. There is, however, a drawback to utilizing H_2 as a fuel source in terms of increased emission of NOx at high combustion temperatures, and additional technology must, therefore, be incorporated for proper emissions management [76].

5.3.1 Torque and power

The heating value of diesel is 43.6 MJ/kg, while petrol has a heating value of 43.4 MJ/kg, significantly lower than hydrogen's heating value of 120 MJ/kg, H_2 is often used as an additive in SI and CI engines, but this frequently causes reduction of the engine's volumetric efficiency [77]. Hydrogen's property of expanding much more significantly in comparison to liquid fuels, which, in the process, constrains the adequate capacity of the combustion chamber designed explicitly for mixtures of air and fuel. In addition, intake manifold heating, conventionally designed for vaporizing liquid fuels such as gasoline and diesel, worsens the problem [78].

Reducing volumetric intelligence when using hydrogen fuel in an ICE will reduce engine torque and power. Compression Ignition (CI) engines lose power and torque by adding 25% and 50% hydrogen blends, as shown in Figure 9. The same situation has been presented for petrol engines using hydrogen as an additive. The lower volumetric energy density can explain the cause of the decrease due to the physical properties of hydrogen, which expands more than liquid fuels, thus shrinking the engine energy available to produce power and torque [79].

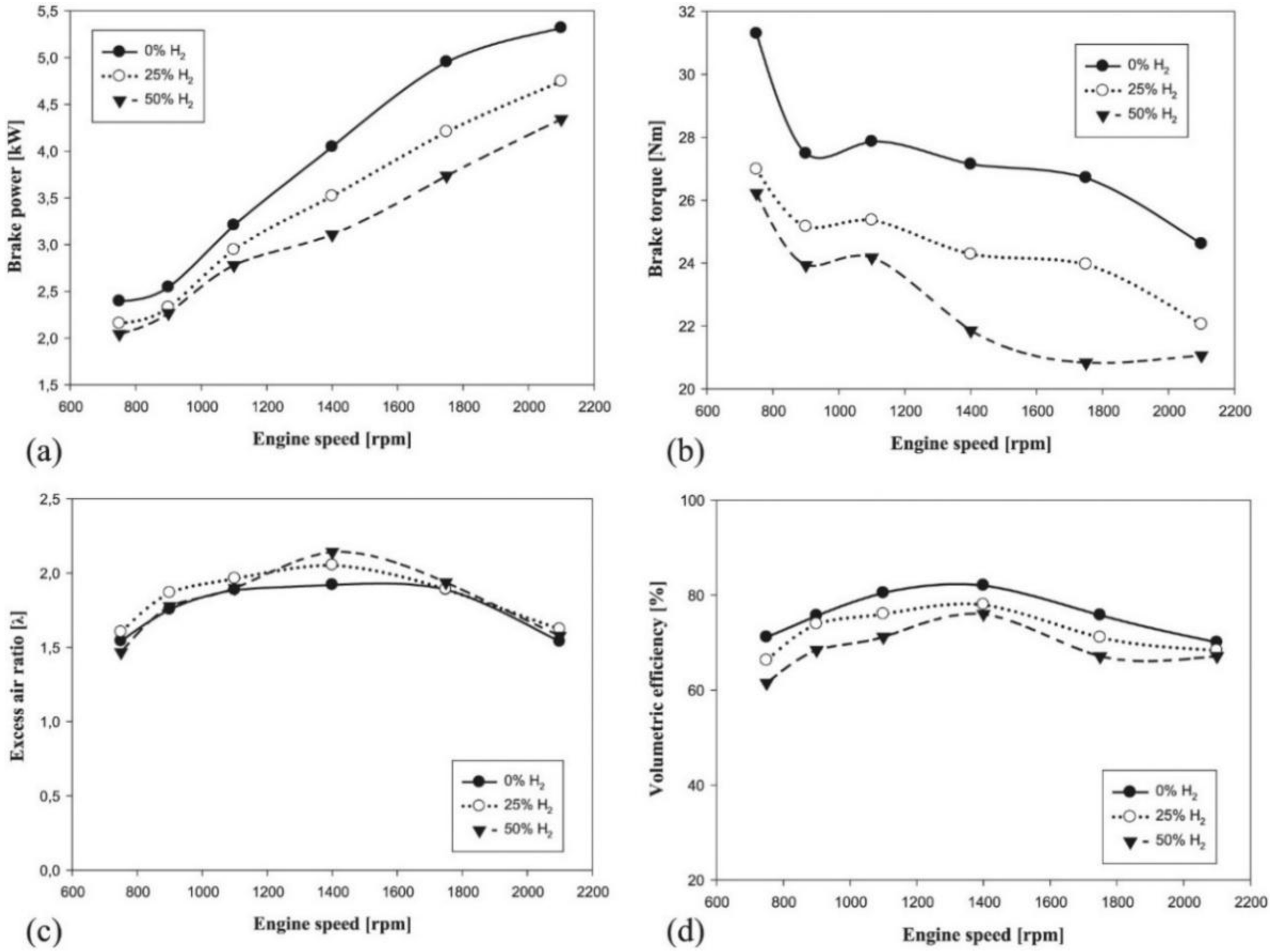
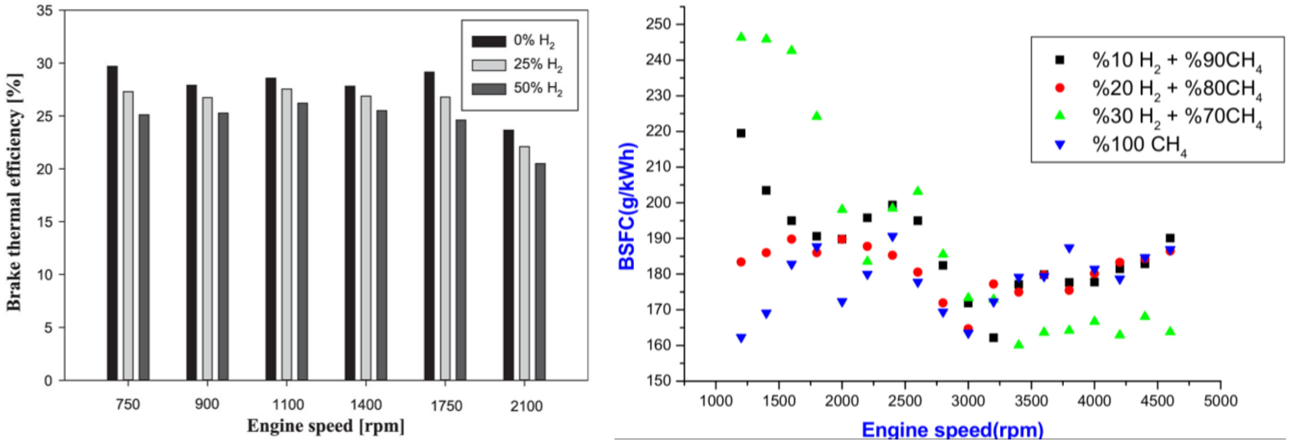


Fig. 9. (a) Variation in braking power, (b) braking torque, (c) excess air ratio, and (d) volumetric efficiency as functions of engine speed and hydrogen flow rate [1]

5.3.2 Brake thermal efficiency

The considerable thermal molecular capacity of hydrogen and its impact on phases of combustion transition can potentially lower combustion efficiency when hydrogen is added to ICE, both spark ignition (SI) and CI types [1]. As a result, this creates a tendency for a drop in such an engine's Brake Thermal Efficiency (BTE). Such a decrease in BTE can be attributed to hydrogen's fundamental properties, which alter combustion dynamics and lead to inefficient energy extraction from the fuel [80]. The effects of hydrogen-enriched fuel on BTE and CI engines are illustrated in Figure 10. It is observed that in the case of CI engines, hydrogen addition in base fuels such as diesel is responsible for reduced BTE.

Other studies have also documented such drops, supporting the idea that hydrogen added to a fuel mixture can harm thermal efficiency in an engine under certain circumstances. Figures 10 (a) and Figures 10 (b) present a drop in fuel BTE in a hydrogen-supplemented methane-based spark ignition (SI) engine. Several dimensions of hydrogen fuels have been under investigation, specifically focusing on hydrogen supplementation in fuels with disparate operational behavior. One key variable that warrants evaluation is a change in compression ratio. Existing studies have proven that engines with high compression ratios have been seen to exhibit increased thermal efficiency in addition to a rise in power output are taken from [81-83]. As such, one approach to mitigate power loss in hydrogen-fueled engines is to improve the compression ratio. Several studies have documented that a rise in the compression ratio maximizes combustion efficiency and helps improve BTE, counteracting hydrogen integration's detrimental impact on overall efficiency in an engine.



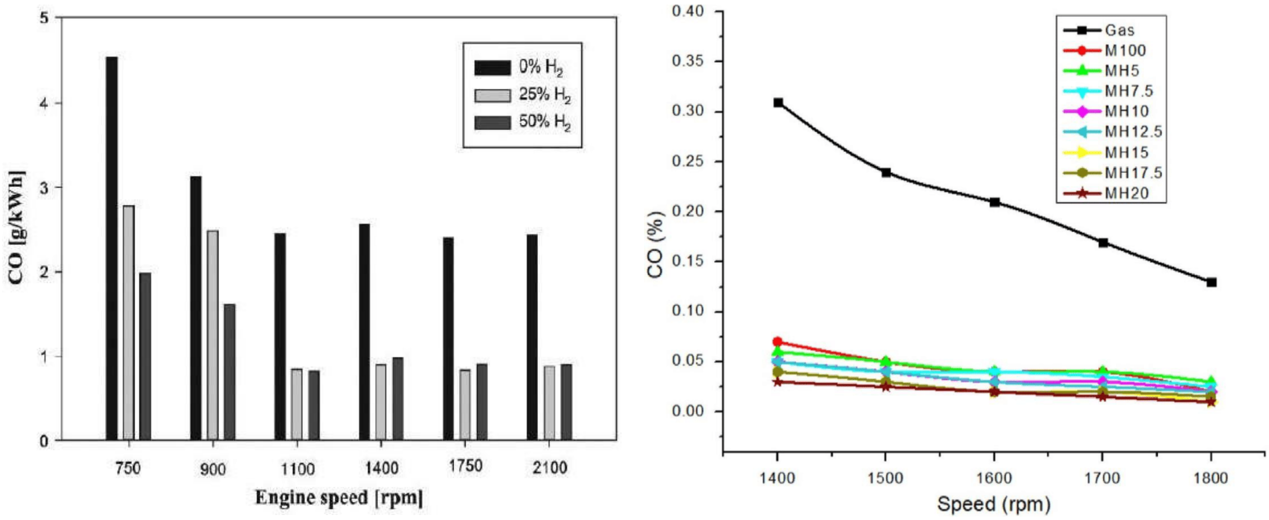
(a) (b)

Fig. 10. (a) Effect of adding 25% - 50% H_2 percentage at engine speed on braking efficiency [1] and (b) Effect of ICE speed on braking efficiency with different treatments of hydrogen and methane addition [77]

5.3.3 Emission (CO and CO_2)

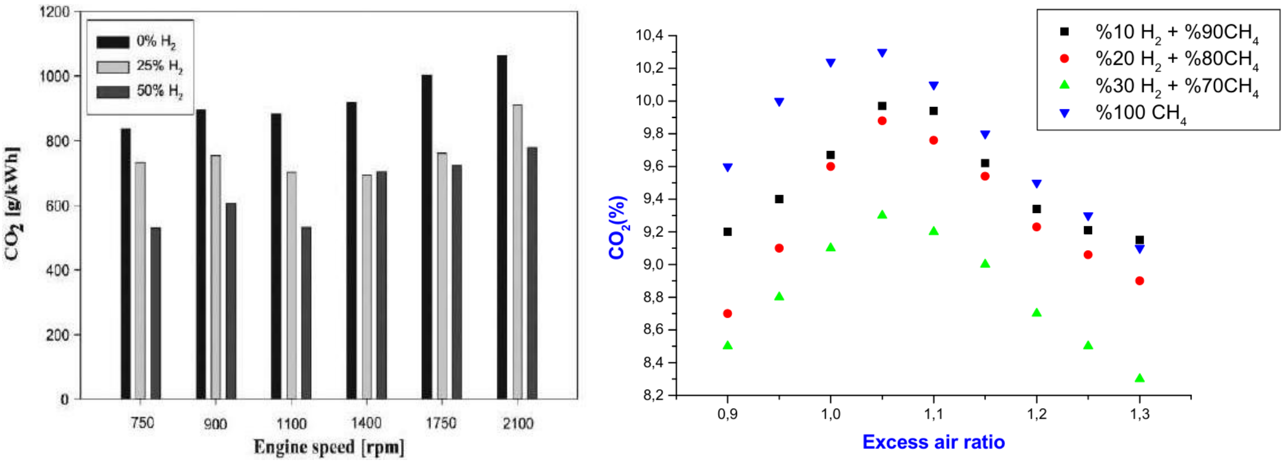
Emission CO and CO_2 are serious environmental problems as they can damage the ozone layer and human health [84]. Incomplete combustion (CI) in ICE can produce CO [85]. Despite this, hydrogen integration in an internal combustion engine can significantly reduce carbon monoxide emissions. Because of its molecular structure, hydrogen cannot be considered a hydrocarbon fuel as it does not have any carbon in its molecular structure; therefore, an increased proportion of hydrogen in the fuel mixture reduces unburned hydrocarbon emissions and, in consequence, minimizes the level of CO emissions [86].

Figures 11 (a) and (b) show some examples of the reduction in carbon monoxide emissions in diesel and gasoline engines using hydrogen as fuel. The production of CO_2 can occur under low oxygen or low-temperature conditions in the combustion chamber, and such can cause incomplete combustion. The emission of CO_2 is unhealthy for the environment and is a key cause of global warming processes [87]. However, using hydrogen as an alternative fuel in ICEs will lead to an increase in the hydrogen-carbon ratio, reduced combustion duration, and improved combustion efficiency [88]. Hydrogen can be defined as a clean fuel source, and its combustion does not produce CO_2 through its lack of carbon content. Thus, the use of hydrogen can cause a significant reduction in CO_2 emissions [89]. Several studies have supported such a drop in CO_2 emissions, and Figures 12 (a) and (b) illustrate a drop in carbon dioxide emissions in hydrogen-fuelled engines.



(a) (b)

Fig. 11. (a) CO emission control by using hydrogen fuel in diesel engines with different percentage cases [1] and (b) CO emission control by using different fuels in diesel engines with different speeds (rpm) [90]

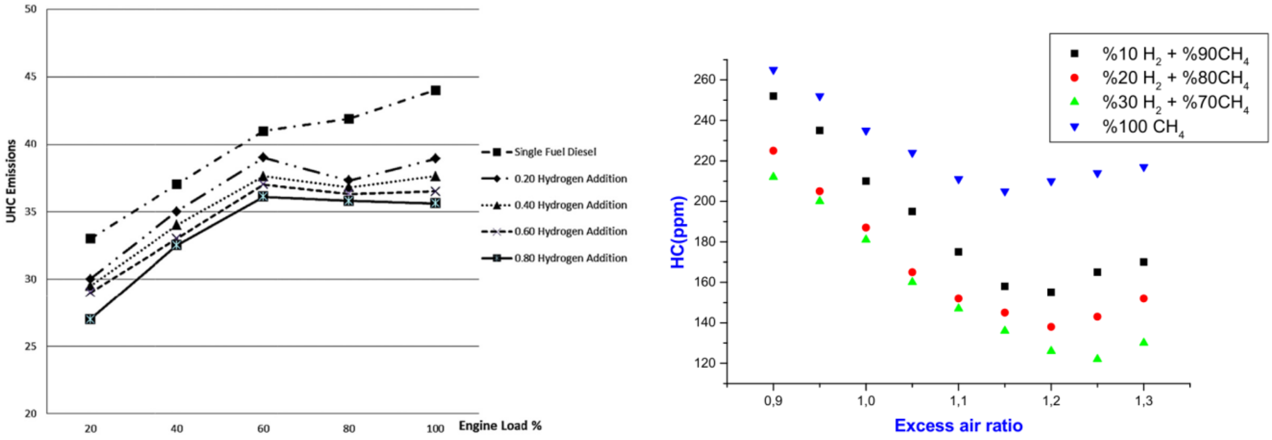


(a) (b)

Fig. 12. (a) CO_2 emission control by using hydrogen fuel in diesel engines with different percentage cases [1] and (b) CO_2 reduction percentage of excess air ratio [77]

5.3.4 Hidro carbon (HC) emission

Unburned hydrocarbons released in the combustion chamber combustion result in unburned hydrocarbon (UHC) emission in the exhaust gas [92]. As stated previously, adding hydrogen to the fuel mixture will assist the mixture in becoming more homogeneous and improve the flame speed, which, in turn, will increase combustion efficiency [93]. In addition, because hydrogen itself does not have any hydrocarbons, its addition will diminish the level of unburned hydrocarbons produced in the combustion process. Therefore, using hydrogen as a fuel will reduce UHC emissions [94]. This reduction in unburned hydrocarbon emissions can be observed in Figures 13 (a) and (b), where the amount of UHC is reduced in diesel and gasoline engines using hydrogen as a fuel additive.

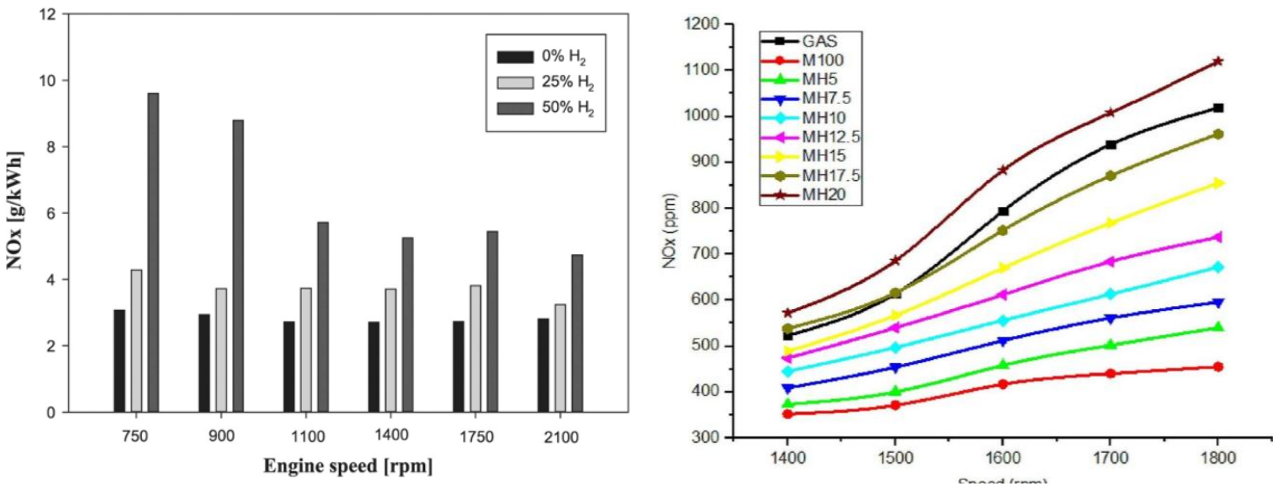


(a) (b)

Fig. 13. (a) The influence of H_2 addition in reducing HC emissions in a single-fuel diesel engine [91] and (b) H_2 and CH_4 variation added with its impact on excess air ratio [77]

5.3.5 Nitrogen oxide emission

High temperatures in the combustion chamber will result in NOx, wherein nitrogen in the air reacts with oxygen due to heat. The NOx emissions are a function of air or fuel mixture, compression ratio, engine speed, ignition timing, and thermal dilution [95]. Hydrogen is an ideal fuel for combustion because it has a high flame velocity, low ignition energy requirement, and high adiabatic temperature, characteristics above increase the temperature of the working fluid inside a cylinder and contribute to NOx emission [90]. Figures 14 (a) and (b): Graphs showing variation in NOx emissions from internal combustion engines using hydrogen. This point refers to the barter economy as a means to describe the framework that laboratories need to establish and discuss the challenges it presents in a fuel-based economy.



(a) (b)

Fig. 14. Graph of speed (rpm) against NOx emissions (ppm) produced, with different hydrogen mixture treatments [1], and Graph of speed (rpm) against NOx emissions (ppm) produced [90]

5.3.6 Smoke emission

Smoke is a characteristic emission of diesel engines, which results from combustion with a non-uniform ratio of fuel and air [96]. Due to the heterogeneous nature of combustion, diesel engines can only endure considerable differences in the distribution of fuel or air ratios present in the cylinders. High hydrogen emission coefficient and access to more excellent oxygen in the combustion process would make the fuel mixture more homogeneous and highly combustible [97]. This implies that there will be an increased amount of hydrogen-carbon ratio contained in the entire fuel, a factor that can be exploited to reduce soot formation in diesel engines [98]. Hydrogen's cleaner and more efficient combustion properties can reduce soot formation. Figure 15 gives one example of decreased soot emissions from a diesel engine due to using hydrogen as an additive fuel. The hydrogen forms a complete combustion that prevents soot particles from building up, which is common in incomplete combustion.

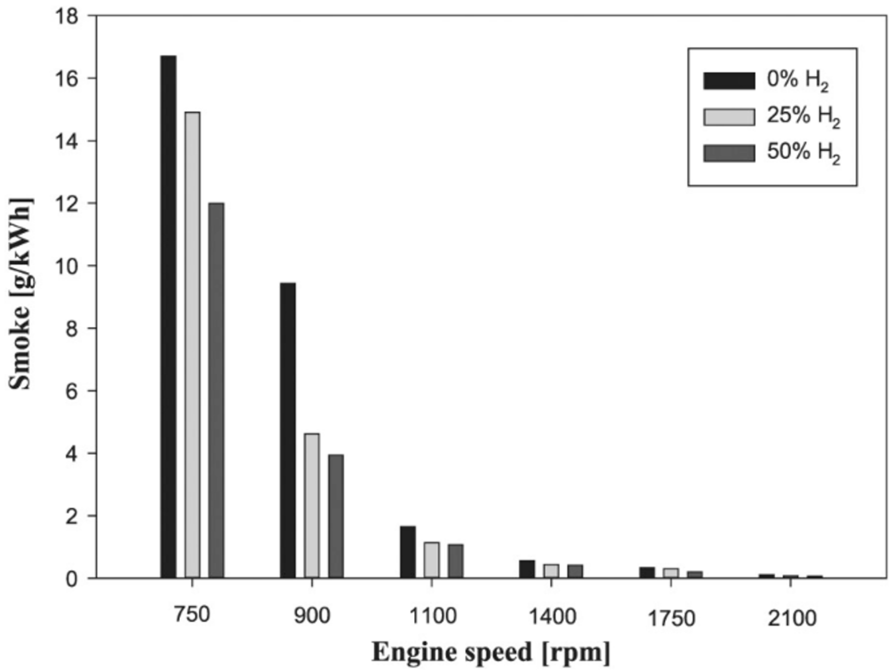


Fig. 15. Graph of engine speed (rpm) against smoke (g/kWh) produced [1]

6. Analysis of Internal Combustion Engines and Fuel Cell Technologies

Comparasion of ICE and fuel cell shown in Table 6. Most of the time, ICEs are very cheap engines well-known, but they cannot make them efficient from the standpoint of how thermodynamics has limited theirs properties [99]. Typically, a power output of 20-30% by the fuel has been translated into useful work, while the rest is wasted as heat [99]. Diesel engines indeed have extremely high thermal efficiency greater than 50% applicable in larger maritime applications. Yet, this has hindered the achievement of emission standards with many other cases and poor fuel usage. These hybrid engines can take advantage of the engine efficiency improvement offered by integration of ICEs with electric motors and batteries, but most human combustion still commonly involves the fossil fuels [99]. Similar improvements on this commercial combustion technology have also been included in the electrification process in the engines [99,100]. The most hybrid engines coupling with electric motor use energy savings as much as 21-28% [99,100]. Energy consumption increases from combustion of IC engines for emission control methods such as those adapted for the reduction of nitrogen oxides and particulates [100].

Meanwhile, fuel cells are designed with such efficiency in mind that their emissions will be fewer. As an example, a fuel cell produces energy via an electrochemical process from the chemical energy of fuels such as hydrogen and converted to electricity, without combustion [100]. This could and can yield efficiencies of above 60%, really depending on which type of cell and under what operating conditions. Increased fuel efficiency in the internal combustion engine stimulated a lot of research from the emission mandates. It is also worth noting that nonrenewable hydrogen in a vehicle produces little or no emissions improvement compared with the best-performing hybrid internal combustion engine [100]. In the field of surface pollutants, ICEs have the maximum quota with respect to all kinds of gaseous air pollutants such as oxides of nitrogen, particulate matter, carbon monoxide, hydrocarbons, and most importantly, a very big number of greenhouse gases including carbon dioxide.

Table 6
Comparison of internal combustion engines and fuel cells

Metric	Internal combustion engine (ICE)	Fuel cell
Efficiency	20-30% (gasoline), up to 50% in advanced designs	40-60%, up to 80% in CHP (Combined Heat and Power) applications
Emissions	High levels of NOx, PM, CO, HC, and	Near-zero emissions with hydrogen fuel (H_2O and heat), emissions depend on the hydrogen source
Operational costs	Mature fuel infrastructure, lower fuel costs, higher maintenance costs	High hydrogen production and distribution costs, lower maintenance costs

7. Challenges in Adoption

Although hydrogen as an alternative fuel promises low greenhouse gas emissions in the shipping industry, the use of this technology still has many obstacles that must be overcome for successful and large-scale adoption. Table 7 has summarized the benefit and challanges of hydrogen fuel use. Despite the challenges, the prospect of clean and renewable energy from hydrogen makes it a viable energy source for reducing GHG in the maritime sector. Therefore, to achieve the common goal of managing and optimizing hydrogen use in the industry, various stakeholders in the industry must engage in active research, technology development, and regulatory changes to ensure that hydrogen is used throughout the industry in a broad and sustainable manner.

Table 7
Benefit and challenges of hydrogen use [101]

Benefits	**Challenges**
Can be produced using renewable energy	The limited supply of hydrogen generated from renewable sources
Devoid of emissions that include but are not limited to carbon, sulfur, GHGs, and particulate matter	Burning fuels in internal combustion engines (ICEs) causes the release of NOx emissions.
Can be stored and transported in liquid or gaseous form	Vulnerability to leakages, fluid flow through porous materials and ductility of substances
Remarkable buoyancy and the capacity to spread in case of a rupture, if not more, even at the conditions of liquefied hydrogen temperatures.	High risk of explosion in constricted spaces
Fuelled by hydrogen, these cells are soundless, possess no mechanical movers, are very easy to enlarge, and can be installed in most ships.	The exorbitant expenses tied to renewable hydrogen and the substantial capital investment needed for fuelling logistics and storage.

7.1 Energy Density and Hydrogen Storage

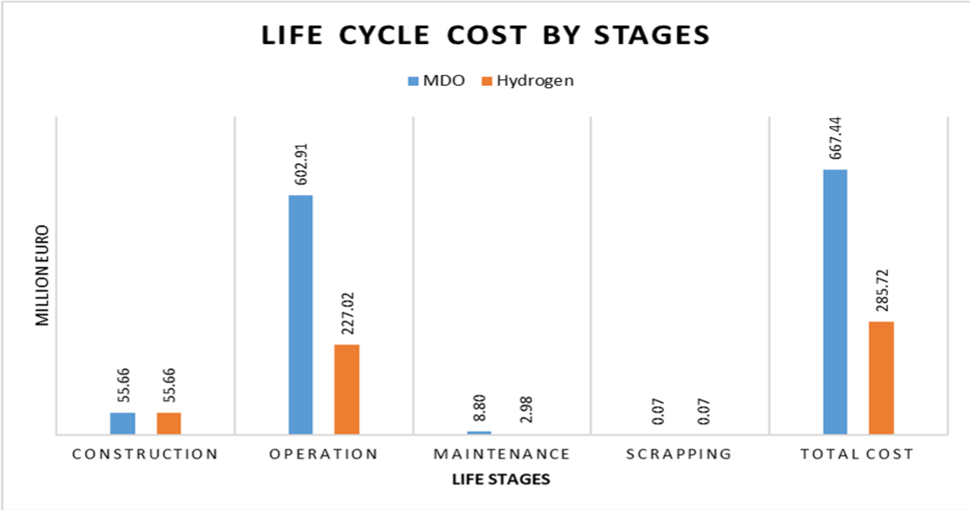
Under standard conditions, hydrogen has a low volumetric energy density, hence making it necessary to use efficient storage methods for hydrogen in the maritime sector [102]. Modalities frequently employed in hydrogen storage are pressurized stores, storage in the form of cryogenic liquids, or storage within adsorbent liquids or solids. The pressurized gaseous hydrogen storage, however, requires space of very large volumes, especially for long-range vessels with huge energy requirements, which can be a limiting factor in generating a ship design [103]. Storing hydrogen in a liquid form at cryogenic temperatures is one of the best alternatives available. This approach permits the concentration of hydrogen gas more productively in compact dimensions, which eases the propulsion of vessels with high energy requirements while maximizing cargo space and efficiency. Hence, it is paramount to choose the most efficient hydrogen storage technology regarding hydrocarbon fuel substitution in marine vessels.

7.2 Safety and Infrastructure

The new bunkering infrastructure should be developed with the necessary safety monitoring to allow for the safe operations of hydrogen carriers on vessels. Hydrogen has quite different characteristics compared to conventional fuels, it has a wider flammability envelope and lower ignition energy, which means that safety must be handled differently [104]. Therefore, supporting infrastructure such as refueling systems, leak detection systems, and emergency procedures must be well thought out because they come with hydrogen risks [105]. Also, training personnel and the relevant stakeholders is important in understanding the risks involved and the importance of safely handling hydrogen. By addressing these concerns in an effective manner in relation to infrastructure that would be developed and implemented for safety purposes, the maritime industry should be able to embrace the use of hydrogen as a clean fuel with little risk involved [106].

7.3 Costs and Methodologies of Hydrogen Generation

Hydrogen production from renewable sources still requires significant technological and infrastructural enhancement and entails higher costs than traditional fuels. Green hydrogen, which refers to hydrogen produced using only renewable energy sources for electrolysis, involves significant capital expenditure on electrolysis systems and renewable energy [108]. While a lot of promise is correlated with green hydrogen, particularly in making the case for clean energy transition, the technology is still under research and development and has not yet matured enough for commercial use [109]. Furthermore, the barriers to entry of hydrogen as an alternative fuel also include high initial expenditure on electrolysis systems and related infrastructures [110]. Hence, it is vital to invest a lot in research and development, along with implementing policies that can aid in reducing production costs as shown in Figure 16 and enhancing technology efficiency for hydrogen to be able to compete favorably in the global energy market [109].



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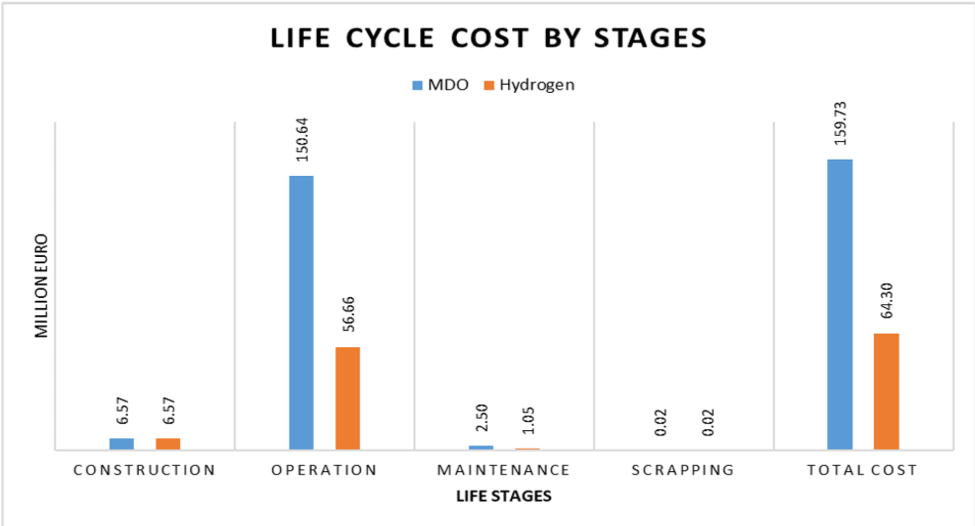

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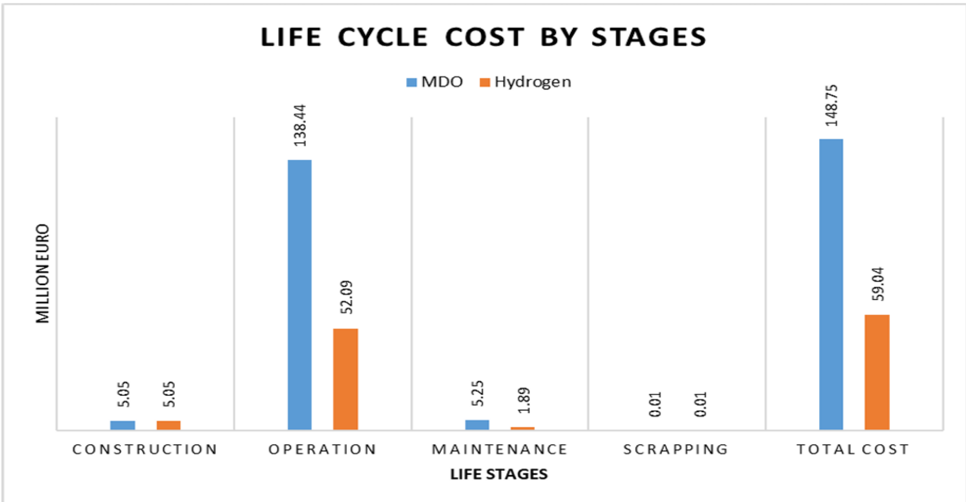


(c)

Fig. 16. Life cycle cost impacts application in maritime transport (a) Mainland ferry, (b) Pelagic trawler, and (c) Interisland ferry [107]

7.4 Procedure and Policies

Incorporating hydrogen technology in the maritime industry will certainly require some modification of the existing practices, codes and safety standards already in place, as certain peculiarities need to be addressed while working with hydrogen. The fluid, unlike others, possesses some traits such as wide flammability strata and high chances of leakage; hence, modifications of some set of safety protocols and standard operating procedures must be carried out. There is a need for amendment of the existing legislation regarding the use of appropriate infrastructure for hydrogen storage, transfer and usage, in addition to ensuring that the facilities and systems related to the operations are of high standards [112]. Figure 17 summarizes the policies proposed by key international stakeholders regarding hydrogen (H_2) in the maritime or transport sector. Furthermore, engaging all relevant parties, such as maritime management bodies, existing hydrogen businesses, and the shipping sector, is critical for formulating practical guidelines. This, in turn, means that once sufficing standards and vagueness are put in place, the maritime industry is likely to accept hydrogen as a suitable fuel, inclusively speeding up the transition to a greener energy system in a cleaner manner [113].

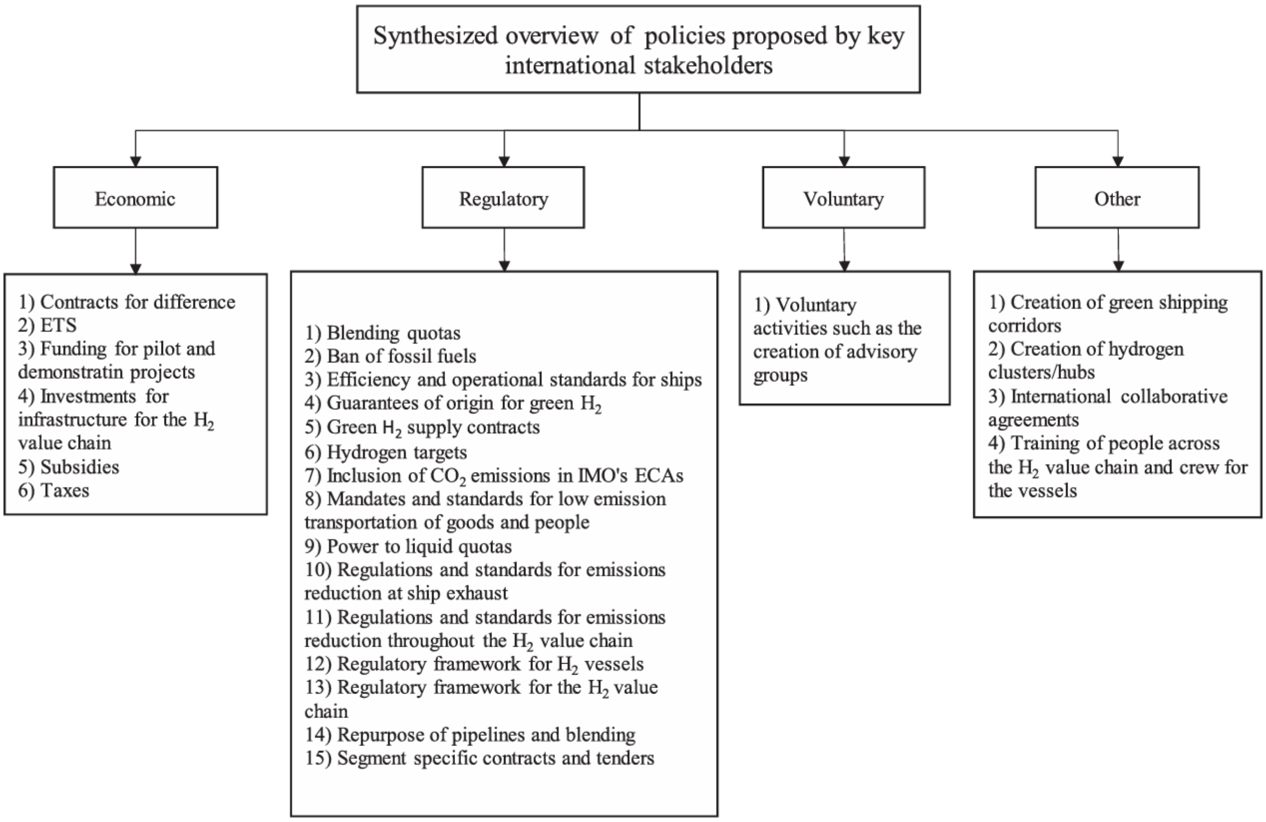


Fig. 17. policies proposed by key international stakeholders regarding hydrogen (H_2) in the maritime or transport sector [111]

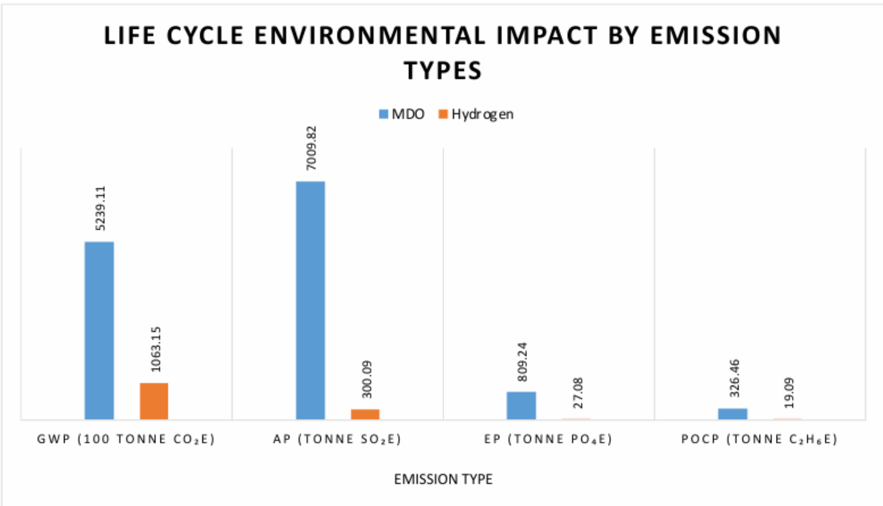
7.5 Regulations and Standards

Adjustment of the applicable regulations, codes and safety standards becomes inevitable when hydrogen technology is introduced into the maritime industry. Generally, the properties of hydrogen differ to a larger extent from the properties of conventional fuels, raising the issues of fire and leakage, for instance, thus the need for laws that govern the safety practices of handling, storing and even using hydrogen. Current safety measures in place are to be reviewed and modified to include operational procedures unique to hydrogen, such as arranging the bunkering facilities, refueling procedures, and training personnel. To this end, stakeholders, including maritime authorities, hydrogen producers and vessel operators, must work together to develop suitable and workable guidelines. In the presence of appropriate regulations and standards, hydrogen as an eco-friendly alternative fuel can be embraced by the maritime sector, thus aiding the industry's efforts in reducing emissions and promoting sustainability [106].

8. Enviromental Impact

Hydrogen gained from clean energy sources, like any geothermal energy, needs less transporter CO_2 emissions per ton-kilometre than heavy furnace oil. The process of making hydrogen through the electrolysis of water with electricity from renewable energy sources decreases total greenhouse gas emissions and is based on ethically responsible and sustainable natural resources. Regarding maritime transportation, incorporating hydrogen can remarkably lower the emissions associated with ships, making it a greener alternative to cargo transport. Moreover, the replacement with green hydrogen is one of the options in line with the longer-term tendencies for decarbonization of the economy, which is foremost a shift towards cleaner energy for the maritime sector and the fulfillment of environmental concerns that the industry is faced with in the form of legislation on emissions.

Hence, hydrogen produced from locally available energy resources is not simply environmentally friendly but also possesses merit for the transportation industry through increased productivity [114]. Figure 18 is a real case example of the use of hydrogen as a ship fuel in various types of ships. Meanwhile, there is a diversity in the level of ecological toxicity caused by the range of activities and marine resources affected, which increases the level of hydrogen production processes used, as shown in Figure 19.



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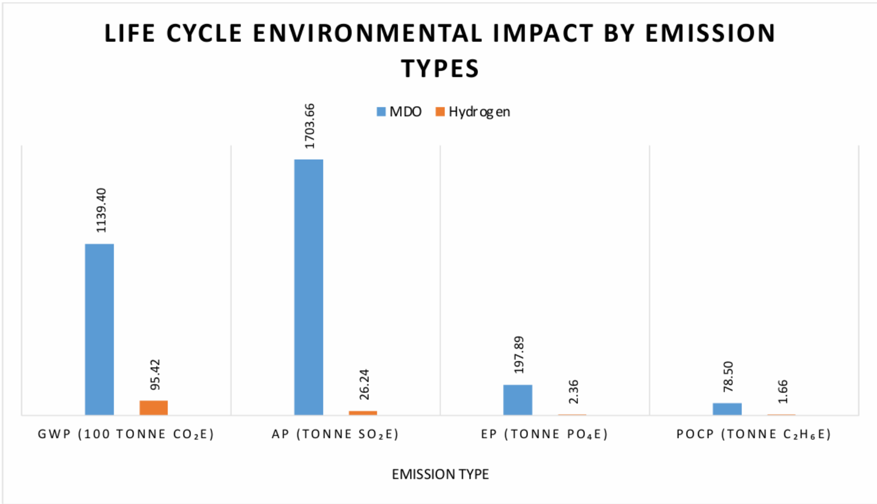

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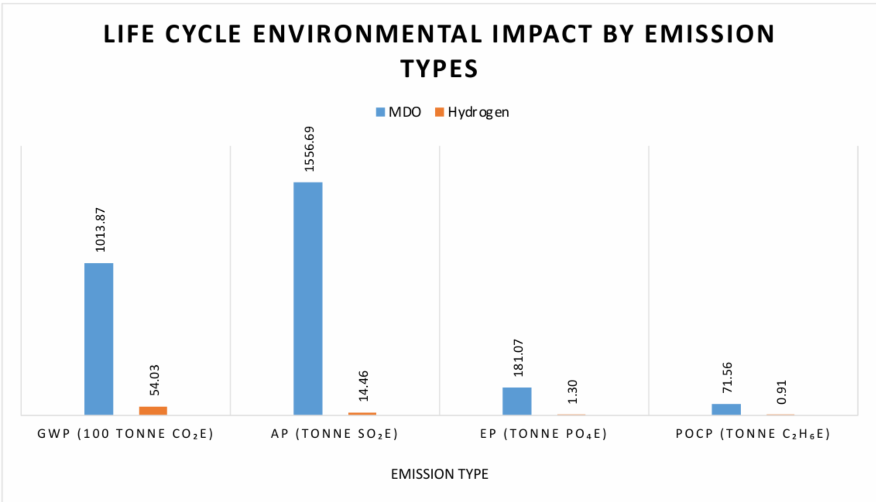

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Fig. 18. Life cycle cost impacts application in maritime transport (a) Mainland ferry, (b) Pelagic trawler, and (c) Interisland ferry [107]

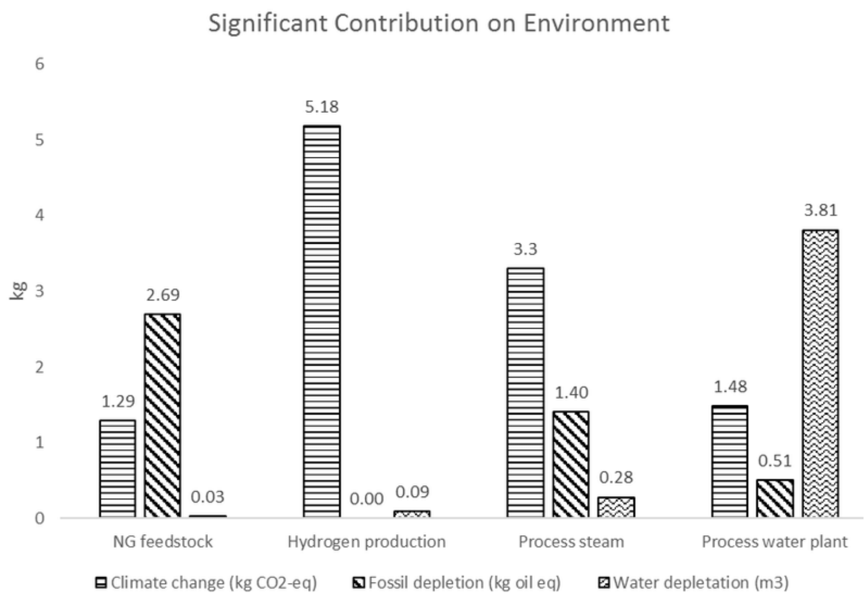

Fig. 19. Environmental impact results for the most significant impact category [24]

9. Conclusion

These hybrid systems, such as hydrogen fuel cells in combination with traditional engines or additional renewable energy solutions, may provide the right path to more efficacious performance and reduced emissions. Future research should focus on hydrogen storage materials, improving the efficiency of fuel cells, and optimizing engine combustion, so future work may concern the study of hydrogen. It will also be important to develop rigorous safety precautions to limit the flammability risk of hydrogen, particularly in maritime applications.

Hydrogen will become a fuel that may, in terms of environmental benefits, reduce emission of greenhouse gases up to the level of 40% when it is blended with conventional fuels and will eliminate CO emissions if used in fuel cells technology. Fuel cells, including the PEMFC, can achieve efficiencies as high as 60% and thus can be considered a promising alternative to the ICE for maritime applications. It has the additional advantage of using hydrogen in different forms such as compression, cryogenic storage, or electrochemical storage for a number of operating needs which reduces dependence on fossil fuels and assures energy security, thereby progressing towards the sustainability goals.

Much promise surrounds widespread use of hydrogen, but many obstacles still stand in its way: production, storage, and distribution are expensive because of limited infrastructure; safety risks because of hydrogen's flammability and the fact that it requires specialist technology solutions are another major hurdle. At the technical level, the two major hurdles to the use of hydrogen are NOx emissions from hydrogen-fueled engines and a certain degree of degradation of fuel cell membranes while operating. More than that, hydrogen is characterized by a high value of gravimetric energy density but in contradiction, with low volumetric energy density providing good efficiency and storage capacity in shiploads long. This, in turn, will also reduce the competitiveness of hydrogen with conventional fuels in particular applications.

Acknowledgement
The Indonesian Ministry of Education, Culture, Research, and Technology funded this study through the PMDSU program. The Institut Teknologi Sepuluh Nopember (ITS), which continuously supports several research projects and related facilities, also provided partial support (2158/E4/DT.04.02/2024).

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