

Comparative Evaluation of Hydrogen with Other Conventional and Alternative Marine Fuels

Caglar Dere¹, Omer Berkehan Inal²

In the pursuit of reducing greenhouse gas emissions and meeting sustainable energy demands worldwide, renewable and alternative energy sources are becoming increasingly effective instruments. The transportation sector remains a significant source of emissions, with fossil fuels serving as the primary propulsion fuel in maritime transportation due to the widespread use of internal combustion engines in ships. To mitigate the impact of maritime transportation on climate change, reducing fossil fuel dependency in internal combustion engines can contribute to decarbonization in the maritime sector. In this context, hydrogen, a carbon-free fuel, presents a promising solution. It can be used in internal combustion engines through a dual-fuel approach rather than direct combustion, helping to address the limitations of hydrogen combustion while allowing hydrogen to partially replace conventional fuels. This study examines alternative fuels that could be used as marine fuels alongside hydrogen in internal combustion engines, focusing on their combustion performance characteristics. The paper aims to establish criteria for selecting suitable marine fuel sources. A gap analysis is conducted on the compatibility of hydrogen with alternative fuels in marine engines, considering performance characteristics such as combustion duration, efficiency, in-cylinder pressure and temperature, and emissions. Although diesel and natural gas are not classified as renewable fuels, their compatibility with hydrogen makes them viable candidates. Hydrogen-enriched operations could improve the combustion characteristics of internal combustion engines running on alternative fuels.

KEY WORDS

Hydrogen
Combustion characteristics
Emission reduction
Marine engineering
Alternative fuels

¹ Izmir Katip Celebi University, Faculty of Naval Architecture and Maritime, Department of Marine Engineering, Izmir, Türkiye

² Istanbul Technical University, Maritime Faculty, Marine Engineering Department, Istanbul, Türkiye
e-mail: inalo@itu.edu.tr

doi: 10.7225/toms.v14.n03.008

Received: 1 Feb 2025 / Revised: 8 May 2025 / Accepted: 23 Aug 2025 / Published: 21 Oct 2025

This work is licensed under 

1. INTRODUCTION

The growing focus on global warming has prompted all industrial sectors to seek clean energy sources to achieve environmental protection goals. As a result, the shift from traditional carbon-based fuels to alternative fuels has advanced significantly in recent years. However, the energy transition still lacks momentum in most sectors, including maritime transportation. According to the International Maritime Organization's (IMO) 4th Greenhouse Gas (GHG) Study (IMO, 2020), maritime transportation accounts for 2.89% of anthropogenic emissions. The shift from traditional fuels to alternatives in the maritime sector is ongoing and gradually accelerating, as shown by the increasing number of vessels using alternative fuels and the introduction of regulations such as the IMO's FuelEU Maritime and CII framework. DNV's Alternative Fuels Insight (AFI) platform reports that the number of ships using alternative fuels more than doubled between 2020 and 2023, underscoring this accelerating trend (DNV, 2023).

To promote GHG emission reductions in the maritime sector, the IMO and various global organizations have implemented several measures, including the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), the Carbon Intensity Index (CII), and the Ship Energy Efficiency Management Plan (SEEMP) (Inal, Charpentier, and Deniz, 2022). These initiatives aim to improve energy efficiency and reduce the environmental impact of shipping. However, while these organizations set target emission levels, they leave the choice of methods for achieving these targets to shipping operators and companies. In this context, adopting alternative fuels along with efficiency-improving measures can help achieve these goals.

The use of alternative fuels in marine engines is widely considered a key option for reducing shipping emissions (Deniz and Zincir, 2016). However, diesel fuel and natural gas remain the main energy sources in marine power plants (IMO, 2020). While natural gas and oil-based fuels are not classified as renewable, alcohol-based fuels and hydrogen blends can be considered renewable energy sources (Yousufuddin and Masood, 2009). The transition to alternative fuels in ships will be gradual due to technical and economic constraints. One of the main technical challenges is the high power required for ship propulsion, which is currently met primarily by internal combustion engines (ICEs). ICEs are a well-established and mature technology in the transportation sector, widely used for their reliability, broad power output range, and high efficiency. Since ICEs dominate ship propulsion systems, they must be included in decarbonization solutions for the maritime sector.

ICEs' ability to operate with various fuels makes hydrogen a significant option for decarbonizing maritime transportation. While hydrogen fuel cell technology is another promising solution for shipping (Yousufuddin and Masood, 2009), ICE technology is already mature and optimized for production costs and materials. In contrast, hydrogen fuel cells, despite their potential for zero-emission power generation, remain an expensive alternative compared to ICEs (Inal and Deniz, 2020; Wang and Wright, 2021). Furthermore, fuel cells require high-purity hydrogen, which may not always be feasible for ships (Inal and Deniz, 2020; Tsujimura and Suzuki, 2017), whereas ICEs can operate with lower-purity hydrogen without major issues. These factors make hydrogen a practical and viable option for use in ICEs in maritime applications.

Hydrogen possesses unique combustion properties compared to other fuels. However, its combustion at high temperatures in ICEs can lead to nitrogen oxide (NOx) formation. While hydrogen's exceptional combustion characteristics can have both positive and negative effects, the negative aspects can be mitigated through appropriate measures, transforming potential drawbacks into advantages (Boretti, 2020). One such measure is the combustion of hydrogen alongside other fuels. Hydrogen's combustion properties provide a considerable advantage when blended with other fuels, facilitating its gradual integration into reciprocating engines and supporting the transition process. Its high flame speed and low ignition energy make hydrogen an effective additive for improving engine performance (Zhen et al., 2020).

With the growing momentum of the dual-fuel concept, higher efficiency and lower emissions can be achieved through an optimized combustion process (Yapicioglu and Dincer, 2018). However, selecting appropriate alternative fuels for marine engines is crucial for sustainable shipping. The chemical compositions of fuels used in internal combustion engines vary, with different carbon, hydrogen, and oxygen ratios by mass fraction. These physical and chemical properties significantly influence emission generation in ICEs. Consequently, different alternative fuels will not exhibit identical combustion behavior when combined with hydrogen.

Hydrogen's zero-carbon content makes it a valuable component in carbon emission reduction strategies for internal combustion engines (ICEs). However, direct hydrogen combustion has drawbacks, including lower volumetric efficiency and lower energy content per unit volume compared to conventional fuels. Additionally, hydrogen supply has not yet reached the scale necessary for a complete transition of ICEs. A partial transition to hydrogen combustion can help advance maritime decarbonization. Studies have shown that hydrogen addition can reduce CO and HC emissions while enhancing lean combustion properties in engines (Anticaglia et al., 2023). Hydrogen is increasingly viewed as a key enabler of maritime decarbonization and is often studied alongside alternative fuels such as ammonia, methanol, and natural gas. Ji et al. (2013) investigated hydrogen addition in methanol-fueled spark-ignition engines, while Abdelalli et al. (2022) studied hydrogen enrichment in natural gas-diesel dual-fuel engines. Zafar et al. (2023) and Lindstad et al. (2021) examined alternative fuels from techno-economic perspectives, and Yapicioglu and Dincer (2018) assessed hydrogen-ammonia blends in power generation. However, these studies typically focus on single fuel combinations or specific engine types. Moreover, while some employ SWOT or PESTLE frameworks (Mahia Prados et al., 2024), they are often limited to policy or environmental assessments without incorporating combustion characteristics. To our knowledge, no study to date has conducted a comparative evaluation of hydrogen blended with multiple marine fuels, assessed through combustion performance metrics and complemented by a SWOT analysis targeting ICE applications. This paper addresses that gap by synthesizing technical and strategic aspects in a unified framework, providing a resource for fuel selection in marine transition planning.

While numerous studies have evaluated individual alternative marine fuels and hydrogen integration, most are limited to single-fuel evaluations or general policy analysis. This study distinguishes itself by conducting a comparative analysis of hydrogen blended with multiple marine fuels—including diesel, LNG, methanol, ethanol, and ammonia—focused specifically on ICE applications. The novelty of this work lies in combining detailed combustion performance metrics with a structured SWOT analysis, offering both technical and strategic insights for sustainable fuel adoption in the maritime sector. The assessment is conducted through a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of various fuel options. This article presents an overview of fuels used in ships, briefly reviews hydrogen's combustion properties in ICEs, and examines how alternative fuels interact with hydrogen in combustion. Modifications in fuel performance characteristics are evaluated, providing insights into the future selection of sustainable shipping fuels.

2. THE FUELS USED IN MARITIME TRANSPORTATION

The main propulsion source for ships is diesel engines, which are classified as low-, medium-, and high-speed engines and account for approximately 98% of commercial ships (IMO, 2020). The expected lifetime of a commercial ship is around 25 years, meaning a significant portion of the current fleet will continue operating for the next 10–15 years. Consequently, it is anticipated that the shipping sector will continue to rely on oil-based fuels in the coming years. In a sustainable development scenario, the International Energy Agency (IEA, 2020) projects that even by 2070, the transportation sector will still have a 14% dependency on fossil fuels, which remain the primary energy source in transportation today. This projection is illustrated in Figure 1. Since the energy transition in small-scale transportation is progressing faster than in large-scale sectors, it can be inferred that the remaining fossil fuel dependency will largely be attributed to the shipping industry.

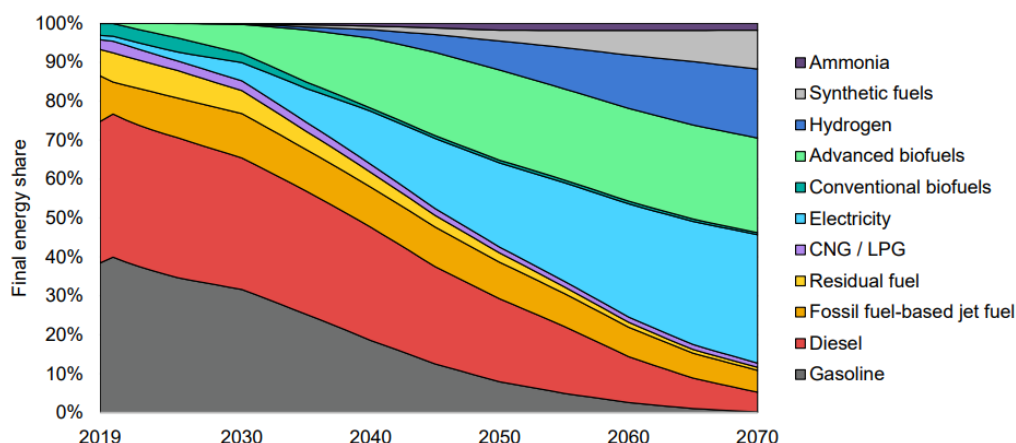


Figure 1. Prediction of global transportation energy sources from 2019 to 2070, reproduced from the IEA report (IEA, 2020).

Despite the significant reduction in fossil fuel demand, there will still be a considerable need for these fuels in the coming years. The growth in electricity demand (shown in blue) is due to the increasing number of electric vehicles. Other rising energy sources, such as biofuels, hydrogen, synthetic fuels, and ammonia, are primarily intended for trucks, ships, and other heavy-duty transportation. Production rate trends are expected to follow similar patterns, with no dramatic shifts anticipated. Therefore, a smooth and balanced transition is projected in this scenario. In the shipping sector, both conventional fuels currently used in existing ships and emerging fuel options for the future are under consideration. While diesel fuel and fossil fuel gases such as natural gas and petroleum gas are widely used in existing ships, alternative fuels—including ethanol, methanol, hydrogen, and ammonia—are being explored and ranked by their maturity level in marine internal combustion engines. To provide a more detailed examination, the physical and chemical properties of both conventional and alternative fuels are presented in Table 1 (Qu et al., 2024; Yip et al., 2019; Zhen et al., 2020). Although alternative fuels are the primary focus in the path toward decarbonization, methane, a major component of natural gas, and diesel, the conventional fuel for much of the existing fleet, are included in the table due to their market dominance and potential to be blended with hydrogen and other alternative fuels. These conventional fuel properties serve as reference values to facilitate comparison. Key parameters such as chemical composition, density, flammability, ignition characteristics, and flame properties provide essential data for evaluating fuel combustion performance.

Property	Hydrogen	Diesel	LNG	Methanol	Ethanol	Ammonia
Molecular formula	H ₂	C _n H _{1.8n}	CH ₄	CH ₃ OH	C ₂ H ₅ OH	NH ₃
Carbon content (mass%)	0%	86%	75%	38%	52%	0%
Hydrogen content (mass%)	100%	14%	25%	12%	13%	18%
Oxygen content (mass%)	0%	0%	0%	50%	35%	0%
Density (kg/m³)	0,0899	830	0,83	795	790	0,7
Lower Heat Value (MJ/kg)	120	42,5	50,05	20,26	27	18,6
Auto-ignition temperature (K)	858	523	813	738	698	924
Stoichiometric air-fuel ratio	34,3	14,5	17,2	6,5	9	6,06

Laminar flame speed (m/s)	2,37	0,37-0,43	0,38	0,52	0,39	0,07
Adiabatic flame temperature (K)	2382	2300	2225	2143	2193	1800
Flammability limits (vol% in air)	4-75%	0.6-5.5%	4-16%	6-36%	3-19%	14.8-33.5%
Min. ignition energy in the air (mJ)	0,02	0,24	0,28	0,14	0,23	680
Quenching distance (mm)	0,6	-	2,03	1,85	1,65	7
Cetane Number	>130	>20	130	<5	5-15	120
Boiling Point °C	-253	>180	-162	65	78	-33
CO₂ emissions	Low	High	Medium	Medium	Medium	Low
SO_x emissions	Low	Medium	Low	Low	Low	Low
NO_x emissions	High	High	Medium	Medium	Medium	High

Table 1. The physical and chemical properties of fuels, reproduced from (Arcos and Santos; 2023; DNV, 2023; Greenwood et al., 2014; Herbinet et al., 2022; IMO, 2020).

Quenching distance values for diesel vary and are not consistently reported due to its complex composition. As seen in the table the fuels have quite different chemical and physical properties which ends up with different combustion properties and emissions. The hydrogen differs from the other fuels with its unique properties and characteristics as flame speed, wide flammability range. These characteristics make hydrogen a perfect fuel to combine with other fuels, in particular its high stoichiometric air-to-fuel ratio (Pan et al., 2014).

2.1. Hydrogen

Hydrogen, as a molecule, is rarely found in the atmosphere, so it must be produced and stored using an external energy source before being used as fuel. These external energy sources include fossil fuels (with or without carbon capture systems), pyrolysis of fossil fuels (LNG), renewable energy, and nuclear energy. Based on their production methods, hydrogen is categorized as gray, blue, turquoise, green, and yellow hydrogen, respectively (Bilgili, 2023; Incer-Valverde, 2023). Gray hydrogen is produced from fossil fuels without carbon capture (Arcos and Santos, 2023); blue hydrogen is produced from fossil fuels with carbon capture and storage (CCS) (Lubbe et al., 2023); turquoise hydrogen is produced from methane pyrolysis, yielding solid carbon; green hydrogen is produced from renewable energy via electrolysis (Schuler et al., 2023); and yellow hydrogen is produced via electrolysis using electricity from the grid (mixed sources) (Inal and Senol, 2024). As an energy carrier, hydrogen is considered a clean and environmentally friendly fuel due to its carbon-free structure. However, the greenhouse gas (GHG) emissions associated with hydrogen depend on its production process. When produced from fossil fuels, hydrogen still contributes to GHG emissions, similar to natural gas (Kim et al., 2020).

Hydrogen has the highest lower heating value (LHV) per unit mass among conventional fuels. Its combustion generates water as the primary byproduct, making it a clean fuel for combustion applications. However, its volumetric energy density is nearly ten times lower than that of methane (Balcombe et al., 2019), making large-scale storage and transportation costly both economically and in terms of emissions. The high specific volume of hydrogen negatively affects volumetric efficiency, which in turn impacts the power output of hydrogen-fueled internal combustion engines (ICEs), especially in external mixture applications (Verhest et al., 2013). Consequently, blending hydrogen with other fuels can facilitate a smoother fuel transition and help mitigate onboard storage challenges for ships, which require large fuel quantities. While pure hydrogen combustion offers advantages in terms of carbon emissions and fuel availability, its production and storage capacities remain key challenges.

In terms of combustion properties, hydrogen has a wide flammability range, high laminar flame speed, and low minimum ignition energy in air, making it favorable for combustion. When mixed with other fuels, hydrogen can enhance flame speed, expand the flammability range, and improve overall combustion quality, making it a viable option for enhancing engine performance (Ji et al., 2013). However, these properties can also result in undesirable combustion characteristics, such as high combustion temperatures, knocking, and increased NO_x emissions. Therefore, combustion parameters must be controlled in ICEs to prevent such issues. Hydrogen's lean combustion capability presents a promising option for improving emissions and efficiency, but insufficient power output remains a significant barrier to pure hydrogen combustion in ICEs. NO_x emissions from hydrogen-fueled engines are highly dependent on the air-fuel ratio (λ); emissions tend to decrease under both excessively lean and rich conditions compared to near-stoichiometric mixtures (Verhest et al., 2013). Nevertheless, hydrogen's wide flammability range (4% to 75%) and high air-fuel stoichiometric ratio allow it to be effectively blended with other fuels (Pan et al., 2014; Verhest et al., 2013). The injection method and phase formation of hydrogen within the combustion process are key considerations. Hydrogen can be introduced using technologies similar to those in gasoline engines. The highest chemical energy input into the cylinder is achieved through direct injection, while cryogenic port injection is another promising alternative compared to conventional port injection (Verhest et al., 2013). Despite the limited number of hydrogen-fueled ICEs, particularly in the maritime sector, advanced technological models and pioneering concepts continue to evolve.

2.2. Diesel Oil

Diesel fuel is the most common fuel used in ships, especially in large-bore marine diesel engines. The carbon content of diesel fuel is determined by the formula specified in Table 1. Heavy fuel oil contains about 85% carbon, while marine diesel oil contains around 87%. The carbon fraction is typically 86% by mass, calculated using the diesel formula C_nH_{1.8n}, as shown in Table 1. Diesel technology is well established, with mature fuel production, supply chain, and storage processes. Diesel engines are classified as slow, medium, or high-speed, with slow-speed marine diesel engines commonly used in commercial ships to burn heavy fuel oil and various diesel fuels. Although diesel fuel is not considered an alternative fuel, its widespread use and potential for blending or dual-fuel operation with hydrogen maintain its relevance in sustainable shipping. Integrating hydrogen with diesel fuel could help reduce carbon emissions in proportion to its energy share.

2.3. Natural Gas

Natural gas, particularly Liquefied Natural Gas (LNG), has gained popularity in recent years due to its relatively low carbon content and cost advantages. Primarily composed of methane (CH₄), its carbon fraction is approximately 75% by mass. In the shipping sector, LNG is favored for its CO₂ reduction potential and lower SO_x and particulate matter (PM) emissions, making it advantageous for meeting short-term regulatory requirements. However, methane slip is a significant drawback for natural gas (Tuswan et al., 2023). Over its entire lifecycle (well-to-wake), including production, transportation, and combustion, LNG's global warming potential (GWP) is not as promising for achieving the IMO 2050 decarbonization targets. The GWP of methane emissions is higher than that of CO₂, and depending on the engine technology (diesel or Otto cycles), LNG's CO₂-equivalent reduction ranges from only 5% to 16% compared to marine distillate fuels (Lindstad, Lagemann, Rialland, Gamlem, and Valland, 2021; Zafar et al., 2023). Additionally, LNG combustion suffers from a slow burning rate, reducing engine efficiency (Tunestål et al., 2002). While LNG engines operate well at high compression ratios and are resistant to knocking (Sapra et al., 2020), hydrogen can be integrated as a solution to mitigate emissions from LNG-powered engines.

2.4. Ammonia

Ammonia (NH_3) consists of nitrogen and three hydrogen atoms, making it a promising hydrogen carrier with a hydrogen content of 17.7% by mass. Although hydrogen has a higher gravimetric energy density (120 MJ/kg compared to 18.6 MJ/kg for ammonia), ammonia offers a higher volumetric energy density. Ammonia is lighter than air, and its evaporation poses health risks. Combustion in internal combustion engines (ICEs) is challenging due to ammonia's low laminar flame speed and limited flammability range in air, as shown in Table 1 (Berni, 2024). Ammonia also has a high-octane number and is highly resistant to autoignition (Herbinet et al., 2002), requiring high compression ratios and temperatures to initiate combustion. However, ammonia performs well when blended with hydrogen, making it a viable alternative for marine engines in dual-fuel mode (Zafar et al., 2023; Otomo et al., 2017). Due to its nitrogen content, ammonia combustion produces NO_x emissions, necessitating after-treatment solutions.

Ammonia can achieve net-zero emissions when produced using renewable energy sources, such as nitrogen and water electrolysis. If fossil fuels like methane are used in its production, carbon capture systems can help reduce emissions. In addition to ICE applications, ammonia can be used in fuel cells, further increasing interest in this fuel. Its onboard storage is more manageable compared to other compressed alternative fuels, though its toxicity poses health risks if inhaled.

2.5. Ethanol

Ethanol, an alcohol-based fuel with a high-octane number, enables higher compression ratios in internal combustion engines (Greenwood et al., 2014). Each ethanol molecule consists of two carbon, six hydrogen, and one oxygen atom, resulting in a carbon fraction of 52% by mass. Ethanol can enhance combustion when blended with conventional fuels, although engine performance may decrease when it is added to gasoline. However, adding hydrogen to ethanol mixtures improves combustion efficiency. The hydrogen-ethanol combination is considered a renewable energy solution, as hydrogen extends the lean combustion limits of ethanol-based fuels (Yousufuddin and Masood, 2009). Additionally, boosted air induction can enable more fuel-efficient operation while reducing emissions. Both ethanol and hydrogen are resistant to autoignition, which may improve engine performance when used together.

2.6. Methanol

Methanol is the fourth most commonly used marine fuel after HFO, MDO, and LNG. Its use in commercial vessels has been increasing since 2015. Methanol is primarily produced from natural gas in a cost-effective manner. Compared to natural gas, methanol offers better storage performance and combustion characteristics. It can be stored at low pressures and relatively higher temperatures, making it more practical than LNG. Compared to heavy fuel oil, methanol combustion reduces CO_2 emissions by approximately 9–10% in converted ships (Zincir, 2023). However, when derived from fossil fuels, methanol's greenhouse gas emissions remain a concern. Methanol is less hazardous to marine ecosystems than ammonia in the event of a spill, though it still poses environmental risks. Its low gravimetric energy density necessitates larger fuel quantities for equivalent energy output. The presence of oxygen in the methanol molecule enhances combustion performance, resulting in fast and complete combustion. Like ethanol, methanol has a high-octane number, improving knocking resistance and allowing higher compression ratios, which enhances engine efficiency. Methanol can be blended with diesel fuel and burned in dual-fuel ICEs (Deniz and Zincir, 2016). Its high latent heat of vaporization improves volumetric efficiency by cooling the intake charge, which is advantageous at high engine speeds but may pose challenges for cold starts and lean combustion operation (Ji et al., 2013).

Based on the technical review provided in previous sections, a strengths, weaknesses, opportunities, and threats (SWOT) analysis was conducted to evaluate the suitability of each fuel type for marine applications. (Lindstad et al., 2021; Zafar et al., 2023; Ellis and Tanneberger, 2015; Mahia Prados et al., 2024).

	Strengths	Weaknesses	Opportunities	Threats
LNG	• Low Carbon Content in per molecule is 25% less) • It reduces SO_x and PM emissions significantly • Cheap and reasonable price • It is not toxic - not corrosive • Regulation and technology maturity	• Lower energy density • Need insulated tanks for storage • Still has, noteworthy carbon content • Methane slip increases the global warming potential • Lack of lean combustion capability	• Cost effective fuel prices • Dual fuel operation capability • Two types of ICE cycle operate as otto and diesel cycles	• Methane slip global warming potential is more than CO₂
Methanol	• Able to reduce CO₂ emissions • Can be cost advantage if it produced from natural gas, on the other side green methanol can be carbon neutral • Better combustion properties, no sulfur emissions • Approved by the IMO, as a ship fuel • Better storage properties compared to LNG	• Lower energy density • The IMO carbon reduction strategy is not met by methanol singularly; only green methanol can be carbon neutral • Additional ignition source is required for the use in ICEs.	• Easy to modify the engines • Technology readiness • Approved as 4th common fuel for ships	• It is toxic for human health • Corrosive effect on specific materials
Ammonia	• Carbon-free structure enables combustion without CO₂, which complies with IMO GHG targets. • Can be produced from renewable sources. • A convenient onboard storage is easily achievable in liquid phase (Lower pressures)	• Lower energy density • It is dangerous for human in the case of exposure • It has poor combustion characteristics in ICEs, (as flame speed) Assistive fuel needed as like pilot fuel • NO_x emissions need after treatment as line SCR. • Bunkering process needs improvement	• Compatible with dual fuel operations. • Fuel prices can be feasible with the increasing renewable energy technologies.	• It is toxic for human health, corrosive effect on the materials • In case, the source of ammonia production based on fossil fuels, still contribute GHG emissions. • NO_x emissions occur as a combustion product, if nitrogen emissions are not regulated properly, the nitrogen cycle can be next problem for climate. • Lack of regulations. • In case of spill, harmful for marine biology
Hydrogen	• Zero emission in combustion, and if produced with renewable energy sources (Green Hydrogen) • High energy density for unit • Non-toxic	• Liquefaction/compression and transportation processes can contribute GHG. • Additional measures needed to reduce NO_x emissions • High Cost	• It is suitable to use with other fuels • Reasonable prices achievable in the future with production techniques • Compatible with ICEs as a fuel	• In case of the production is based on fossil fuels (as LNG) increase GHG emissions (Grey Hydrogen) • NO_x emissions need to be controlled

	• High flame speed • Wide range of flammability • High stoichiometry (air-fuel ratio AFR)	• Lack of technology for combustion in ICE • Low energy density for unit volume • Storage problems in both compressed and liquefied phase. Lack of safety regulations.		
Ethanol	• Environmentally friendly, can be produced by renewable sources • Convenient use in ICE • Nontoxic structure for the environment	• Low gravimetric energy density • Corrosive properties • Low lubricity properties	• IGF code is under development for ethanol fuels.	• Corrosive structure

Table 2. SWOT Analysis of the fuels.

3. COMBUSTION PERFORMANCE CHARACTERISTICS

The operational parameters, such as combustion duration, heat release rate, maximum pressures, peak temperatures, efficiency, carbon emissions, and total heat release, must be considered for fuel combinations in dual-fuel operations.

To begin with, ignition timing influences key parameters such as peak cylinder pressure and temperature, and directly impacts combustion efficiency and emissions. When the ignition timing is advanced, the time interval for fuel injection is reduced, enabling faster combustion due to turbulence in the cylinder (Yousufuddin and Masood, 2009). While fast combustion brings the peaks closer to the top dead center (TDC), timing adjustments in dual-fuel operations must be tailored to the type of fuel and engine operation. It is important to remember that all performance characteristics are interrelated, meaning any change in one parameter affects the others.

Ignition delay is the time interval between fuel injection and the start of combustion, defined as the point at which 10% of the fuel has burned from the spark timing. Ignition timing significantly affects ignition delay. In this study, ignition delay does not depend solely on hydrogen addition; instead, the pressure and temperature of the mixture play a crucial role. The air-fuel ratio is also a significant parameter influencing ignition delay. An insufficient oxidizer can extend the ignition delay period. In scenarios involving hydrogen addition, hydrogen displaces air (including oxygen), reducing the excess air and potentially extending the ignition period of the fuel mixture (Zhen et al., 2020). Ignition delay can be minimized with hydrogen addition. However, as hydrogen displaces air (and thus oxygen), its addition can also increase ignition delay due to reduced oxygen availability.

The heat release rate (HRR) is a key parameter for fuel performance. HRR is defined as the amount of energy released during fuel combustion within a specific time interval, generally measured in crank angle (CA) units. HRR varies with fuel properties and has a dominant effect on pressure and temperature changes in the cylinder during combustion, thereby influencing emissions and efficiency. With hydrogen addition, the HRR curve changes, affecting combustion phenomena, temperature, pressure, and other performance characteristics, either positively or negatively.

Total heat release is obtained by integrating the HRR over the crank angle, representing the total heat energy released from fuel combustion. After accounting for system losses such as friction and cooling, the power output is determined. Hydrogen addition can increase the total heat release of the fuel due to its favorable combustion characteristics, resulting in improved combustion performance.

Combustion duration is the time interval or crank angle range in which 90% of the fuel is burned. It varies based on fuel properties such as flame speed, stoichiometry, and temperature. When combining different fuels, such as hydrogen—which has superior combustion properties—the combustion duration may shorten. This means the same total heat is released in a shorter time, altering the heat release rate. These changes influence in-cylinder pressure and temperature, thereby affecting engine efficiency.

Efficiency, which is also related to specific fuel consumption (SFC), indicates the ratio of work produced to fuel consumed. Internal combustion engines (ICEs) achieve different efficiency rates under varying conditions. Combustion parameters such as heat release, combustion speed, and in-cylinder temperature and pressure variations directly influence efficiency. While efficiency is an important performance indicator, maximum efficiency is not always the primary objective. In some alternative fuel operations, efficiency may be sacrificed to reduce emissions. If the total fuel is burned at stoichiometric ratios, maximum heat per unit volume (kJ/m^3) can be achieved for a given combustible mixture. The highest temperature is reached near stoichiometric ratios on the fuel-rich side. However, excessively lean or rich mixtures result in insufficient heat release, which can lead to incomplete combustion. When combustion is inadequate and heat release is insufficient to ignite the next mixture, propagation reactions terminate, causing poor combustion. Poor combustion is undesirable, but hydrogen's wide flammability and stoichiometric limits help improve emissions by enhancing combustion quality.

Maximum temperature occurs near the point where maximum pressure is reached in the cylinder. The location of this peak is significant for NO_x formation, as NO_x emissions strongly depend on maximum temperature (Saravannan and Nagarajan, 2010). Burning velocity is another important parameter, particularly for fuels such as ammonia and natural gas, which have lower burning velocities. The high flame propagation speed of hydrogen shortens the combustion period as combustion speed increases.

Additionally, the auto-ignition temperature determines how easily a reaction starts. Methanol, ammonia, and hydrogen all have high auto-ignition temperatures. Since additional spark or pilot ignition fuel is needed to initiate combustion, engines in research applications have been converted to spark-ignited engines. Although hydrogen has a high auto-ignition temperature, its very low ignition energy makes it highly prone to ignition from hot engine parts, leading to knocking during hydrogen operation. Combining hydrogen with knock-resistant fuels such as methanol and natural gas, which have high octane numbers, improves combustion performance and extends the knocking limit. Methanol and ethanol, as alcohol-based fuels, have high latent heat, which further enhances knock resistance due to their cooling effect upon evaporation. During the intake process, the evaporation of alcohol fuels improves volumetric efficiency. Alcohol-based fuels also offer advantages such as low viscosity, easy injection, better atomization, improved air mixing, and reduced emissions due to their relatively high hydrogen content and oxygen presence.

4. THE COMPATIBILITY OF THE FUELS WITH HYDROGEN AND DISCUSSION

4.1. Diesel / Hydrogen Combination

Hydrogen addition in diesel engines, provides directly advantage on CO_2 emissions linearly as the energy share of the H_2 increases. Hydrogen doped diesel operation in reduced engine loads come up with less knocking, smoother combustion hence less noise and vibration (Nag et al., 2019). The addition of hydrogen into the diesel engines is on the investigation recently (Serrano et al., 2019; Saravanan and Nagarajan, 2010). The conditions at high loads, diesel engines work relatively high fuel-air ratios, high equivalence ratios, carbon monoxide and hydrocarbon emissions decreases. Compared to the low load operation hydrogen addition performs better combustion efficiency at the high loads (Tsujimura and Suzuki, 2017; Nag et al., 2019). The shorter combustion duration which is heat release in a shorter period causes increment in the peak cylinder pressures and temperatures. NO_x emissions are expected to increase by the addition of hydrogen with high temperatures, however, during low loads and considering the type of hydrogen addition technology, less amount

of oxygen, displaced by hydrogen or reacted, leads to decrease NO_x emissions. On the other hand, NO_x formation does not only depend on the oxygen availability in the chamber, temperature levels and the sufficient time are other parameters that maximum temperature plays a vital role in NO_x formation in ICEs (Saravannan and Nagarajan, 2010).

4.2. Natural Gas / Hydrogen Combination

The LNG fuel is in use in ICEs, reachable fuel with cost and emission advantageous but, it suffers from combustion speed, and the lack of combustion capability which can cause misfiring during low load operations. By the hydrogen addition to the LNG fuel increase the lean combustion capability and improve the combustion speed in ICs. With The laminar burning velocity of the mixture increases as the fraction of hydrogen increase (Abdelalli et al., 2022). The burning velocity helps to reduce combustion duration hence, the higher combustion pressures and higher mean effective pressure can be obtained as the hydrogen content increases (Abdelhameed and Tashima, 2023). The combustion speed of methane is slow and low lean combustion capability makes methane good choice of hydrogen blend to take the hydrogen combustion properties advantages. Hydrogen blend provides smooth and proper combustion. It increases the brake power, thermal efficiency, decrease the hydrocarbon emissions, CO emission, engine fuel consumption (Zareej et al., 2020) and CO_2 emissions with a linear relation methane substitution with hydrogen. However, it also increases the NO_x emissions.

4.3. Ammonia / Hydrogen Combination

The ammonia fuel does not have any sulphur and carbon atoms so any sulphur and carbon emissions is not a combustion product. Ammonia combustion needs additional fuel assist so as to initiate combustion propagation. With the help of hydrogen, having high flame velocity, the combination promotes the ammonia flame speed. As the ammonia amount increase in the combination, the combustion duration and the ignition period increase, the increase in the hydrogen fraction leads to shorten these combustion properties. With the fast combustion process, the brake thermal efficiency and the total output power is expected to increase together with the combustion peak temperatures. However, the hydrogen doped operation affects NO_x emission negatively. In lean conditions, NO_x formation is expected to increase on the other hand, fuel-rich mixture combustion has reverse effect on the production of NO_x emissions. Nitrogen content in the ammonia fuel results with a NO_x emission drawback in the combustion, nevertheless, decreasing the amount of ammonia so means nitrogen atom doesn't result with NO_x reduction by the increasing of hydrogen ratio NO_x emissions increase and compared to ammonia/hydrogen blend to ammonia, NO_x emissions are higher (Xin et al., 2022; Dinesh et al., 2022). Moreover, reducing combustion temperature, adding EGR, and combining with post-treatment technology can be solution in marine engines in the future while practical application is still so limited for ammonia combustion in marine engines.

4.4. Ethanol / Hydrogen Combination

Given their renewability and availability, both ethanol and hydrogen, both of the fuels, ethanol and hydrogen seems a good choice to be combined. When the hydrogen is added to the ethanol fuel combustion capability of ethanol has been improved to gather with the brake power and thermal efficiency (Yousufuddin and Masood, 2009). The primary consequence is reduced specific fuel consumption for the ethanol engine.

Ignition Delay may increase with the lack of oxidizer since the excess air ratio is one of three main parameters has the effect on ignition delay together with in-cylinder temperature and pressure. Maximum in-cylinder pressure may also decrease (Zhen et al., 2020) due to the ignition period increment at the beginning of combustion and the piston movement downwards with the crank angle motion. On the other hand, the fast burning of the mixture reduces the combustion duration can increase the peak pressure (Greenwood et al.,

2014) oppositely to the research (Zhen et al., 2020). The two opposite phenomena can be caused by the detrimental ignition timing, as the ignition timing retards the in-cylinder volume increases by piston movement. The total power output may increase or decrease according to the combustion phenomenon occurrence the rate of heat release of the fuel oxidation. And the amount of hydrogen shares in fuel. Combustion duration may also extend with the increased ignition delay (Zhen et al., 2020) or reduce with rapid combustion (Greenwood et al., 2014). The emissions of CO, CO₂ and HC reduces due to the fuel energy share reduction of ethanol.

4.5. Methanol / Hydrogen Combination

The operation of methanol with hydrogen is generally performed under lean conditions in the literature (Gong et al., 2019). The addition of hydrogen increases brake thermal efficiency (Ji et al., 2013). A wide flammability limit range for hydrogen enables methanol to combust quickly and smoothly, which is the main reason for the observed efficiency increase. Hydrogen allows methanol to burn over a wide range of concentrations. Additionally, hydrogen's high flame speed accelerates methanol combustion, which is otherwise difficult due to methanol's high latent heat. As a result, combustion occurs earlier, near top dead center (TDC) (Ji et al., 2013). Therefore, maximum pressures and temperatures in the cylinder increase, since the cylinder volume is limited near TDC. This condition leads to increased power produced by the piston stroke and higher efficiency.

Other effects of hydrogen addition to methanol include a decrease in hydrocarbon (HC) and carbon monoxide (CO) emissions, and an increase in NO_x emissions, due to reduced carbon-fuel combustion, elevated temperatures, and faster combustion, respectively. The ignition delay can also change in both directions: it may increase due to the reduced amount of excess air with hydrogen addition (Zhen et al., 2020), or decrease due to the ease of hydrogen combustion. Methanol has a cooling effect during the intake process and increases volumetric efficiency. H₂ also has volumetric efficiency issues, which is another advantage in the operation of the fuel combination.

The evaluation of the fuels mentioned above is shown in Table 3, which is reproduced from Yousufuddin and Masood (2009), Tsujimura and Suzuki (2017), Zhen et al. (2020), Ji et al. (2013), Greenwood et al. (2014), Abdelalli et al. (2022), Abdelhameed and Tashima (2023), Huang et al. (2007), and Bayramoglu and Yilmaz (2021). The performance characteristics of combined fuel combustion and their variations are depicted individually; these findings are deduced and concluded by the author based on the studies given in the references.

With H2 doped operation	Hydrogen	Diesel	LNG	Methanol	Ethanol	Ammonia
Flammability range	—	▲	▲	▲	▲	▲
Flame Speed	—	▲	▲	▲	▲	▲
Ignition Delay	—	▼	▼	▼	▲	▼
Thermal Efficiency	—	▲	▲	▲	▲	▲
Power Output	—	▲	▲	▲	▲▼	▲
Peak Temperature	—	▲	▲	▲	▲	▲
Mean Effective Pressure	—	▲	▲	▲	▲▼	▲
Peak Pressure	—	▲	▲	▲	▲▼	▲
Fuel Consumption	—	▼	▼	▼	▼	▼
Combustion Duration	—	▼	▼	▼	▲▼	▼
CO ₂ emissions	—	▼	▼	▼	▼	—
CO emissions	—	▼	▲▶	▼	▼	—
SO _x emissions	—	▼	—	—	—	—

NO _x emissions	—	▲	▲	▲	▲	▲
HC emissions	—	▼	▼	▼	▼	—
▲ = increase; ▼ = decrease; — = no significant change						

Table 3. The hydrogen addition effects on performance characteristics of fuels.

5. CONCLUSION

This study evaluates the effects of hydrogen addition in dual-fuel internal combustion engines, particularly in combination with methanol, ethanol, and methane. The findings indicate that hydrogen significantly affects key combustion characteristics, including ignition delay, heat release rate, and flame propagation speed. Hydrogen addition generally enhances combustion efficiency and reduces carbon-based emissions (CO and HC), but it also increases NO_x formation due to higher in-cylinder temperatures. At low engine loads, hydrogen improves power output by accelerating combustion and increasing volumetric efficiency. However, at higher loads, excessive hydrogen addition can cause knocking, especially in non-alcohol-based fuels such as diesel. This underscores the importance of optimizing injection timing and blending ratios to balance efficiency, emissions, and engine stability. Additionally, while hydrogen's high flame speed and wide flammability range improve combustion, its low ignition energy makes it susceptible to unintended ignition from engine hot spots, posing operational challenges. In summary, hydrogen's role as a secondary fuel presents both opportunities and challenges for future engine development. Its ability to improve combustion efficiency and reduce carbon emissions aligns with global decarbonization goals, but careful fuel management is required to mitigate NO_x emissions and knocking risks. Future research should focus on advanced injection strategies, hybrid fuel combinations, and aftertreatment technologies to enhance the feasibility of hydrogen-assisted dual-fuel operation in marine and heavy-duty applications.

AUTHOR CONTRIBUTION: All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript.

CONFLICT OF INTEREST: The authors declare that they have no known competing interests.

ACKNOWLEDGEMENT: This research was supported by the scientific research projects coordination unit of Izmir Katip Celebi University. Project number is 2024-GAP-GIDF-0008. The authors gratefully acknowledge the support of the research center.

REFERENCES

- Abdelalli, M., Said, M., and Loubar, K. (2022). Investigation of natural gas enrichment with high hydrogen participation in dual fuel diesel engine. *Energy*, 243(x), 122746. <https://doi.org/10.1016/j.energy.2021.122746>
- Abdelhameed, E., and Tashima, H. (2023). Experimental study on the effects of methane-hydrogen jet as direct injected fuel in marine diesel engine. *Energy*, 267(June 2022), 126569. <https://doi.org/10.1016/j.energy.2022.126569>
- Anticaglia, A., Balduzzi, F., Ferrara, G., De Luca, M., Carpentiero, D., Fabbri, A., & Fazzini, L. (2023). Feasibility analysis of a direct injection H₂ internal combustion engine: Numerical assessment and proof-of-concept. *International Journal of Hydrogen Energy*, 48(83), 32553-32571.
- Arcos, J. M. M., Santos, D. M. (2023). The hydrogen color spectrum: techno-economic analysis of the available technologies for hydrogen production. *Gases*, 3(1), 25- 46.
- Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., and Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, 182(December 2018), 72–88. <https://doi.org/10.1016/j.enconman.2018.12.080>
- Bayramoglu, K., and Yilmaz, S. (2020). ScienceDirect Emission and performance estimation in hydrogen injection strategies on diesel engines. *International Journal of Hydrogen Energy*, (xxxx). <https://doi.org/10.1016/j.ijhydene.2020.08.135>
- Berni, F., Pessina, V., Teodosio, L., d'Adamo, A., Borghi, M., & Fontanesi, S. (2024). An integrated 0D/1D/3D numerical framework to predict performance, emissions, knock and heat transfer in ICEs fueled with NH₃–H₂ mixtures: The conversion of a marine Diesel engine as case study. *International Journal of Hydrogen Energy*, 50, 908-938.
- Bilgili, L. (2023). A systematic review on the acceptance of alternative marine fuels. *Renewable and Sustainable Energy Reviews*, 182(August 2022), 113367. <https://doi.org/10.1016/j.rser.2023.113367>
- Boretti, Alberto. "Hydrogen internal combustion engines to 2030." *International Journal of Hydrogen Energy* 45.43 (2020): 23692-23703.
- Deniz, C., and Zincir, B. (2016). Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, 113(X), 438–449. <https://doi.org/10.1016/j.jclepro.2015.11.089>
- Dinesh, M. H., Pandey, J. K., and Kumar, G. N. (2022). Study of performance, combustion, and NO_x emission behavior of an SI engine fuelled with ammonia/hydrogen blends at various compression ratio. *International Journal of Hydrogen Energy*, 47(60), 25391–25403. <https://doi.org/10.1016/j.ijhydene.2022.05.287>
- DNV. (2023). Alternative Fuels Insight (AFI) Platform – Maritime Forecast to 2050. Det Norske Veritas. Retrieved from <https://afi.dnv.com/>
- Ellis, J., and Tanneberger, K. (2015). *Study on the use of ethyl and methyl alcohol as alternative fuels in shipping*. European Maritime Safety Agency (EMSA) (Vol. 46).
- Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., and Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172(2018), 855–866. <https://doi.org/10.1016/j.jclepro.2017.10.165>
- Gong, C., Li, Z., Chen, Y., Liu, J., Liu, F., and Han, Y. (2019). Influence of ignition timing on combustion and emissions of a spark-ignition methanol engine with added hydrogen under lean-burn conditions. *Fuel*, 235(June 2018), 227–238. <https://doi.org/10.1016/j.fuel.2018.07.097>
- Greenwood, J. B., Erickson, P. A., Hwang, J., and Jordan, E. A. (2014). Experimental results of hydrogen enrichment of ethanol in an ultra-lean internal combustion engine. *International Journal of Hydrogen Energy*, 39(24), 12980–12990. <https://doi.org/10.1016/j.ijhydene.2014.06.030>
- Herbinet, O., Bartocci, P., and Grinberg Dana, A. (2022). On the use of ammonia as a fuel – A perspective. *Fuel Communications*, 11, 100064. <https://doi.org/10.1016/J.JFUECO.2022.100064>
- Huang, Z., Wang, J., Liu, B., Zeng, K., Yu, J., and Jiang, D. (2007). Combustion characteristics of a direct-injection engine fueled with natural gas – hydrogen blends under different ignition timings, 86, 381–387. <https://doi.org/10.1016/j.fuel.2006.07.007>
- IEA, I. E. A. (2020). *Energy Technology Perspectives 2020*. *Energy Technology Perspectives 2020*. <https://doi.org/10.1787/ab43a9a5-en>
- IMO, (International Maritime Organization). (2020). *The Fourth IMO GHG Study -Reduction of Ghg Emissions from Ships*.
- Inal, O. B., Charpentier, J. F., and Deniz, C. (2022). Hybrid power and propulsion systems for ships: Current status and future challenges. *Renewable and Sustainable Energy Reviews*, 156(December 2021). <https://doi.org/10.1016/j.rser.2021.111965>
- Inal, O. B., and Deniz, C. (2020). Assessment of fuel cell types for ships: Based on multi-criteria decision analysis. *Journal of Cleaner Production*, 265, 121734. <https://doi.org/10.1016/j.jclepro.2020.121734>
- Inal and Senol (2024). SWOT-AHP Analysis of Different Colours of Hydrogen for Decarbonization of Shipping, *International Journal of Environment and Geoinformatics (IJEgeo)*, 11(2): 029-037. doi. 10.30897/ijgego.1480096

- Ji, C., Zhang, B., and Wang, S. (2013). Enhancing the performance of a spark-ignition methanol engine with hydrogen addition. *International Journal of Hydrogen Energy*, 38(18), 7490–7498. <https://doi.org/10.1016/j.ijhydene.2013.04.001>
- Kim, K., Roh, G., Kim, W., and Chun, K. (2020). A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments. *Journal of Marine Science and Engineering*, 8(3). <https://doi.org/10.3390/jmse8030183>
- Lubbe, F., Rongé, J., Bosserez, T., Martens, J. A. (2023). Golden hydrogen. *Current Opinion in Green and Sustainable Chemistry*, 39, 100732
- Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G. M., and Volland, A. (2021). Reduction of maritime GHG emissions and the potential role of E-fuels. *Transportation Research Part D: Transport and Environment*, 101(November), 103075. <https://doi.org/10.1016/j.trd.2021.103075>
- Mahia Prados, R., Escribano, G. and Arto, I. (2024). Decarbonisation of maritime transport: A comparative SWOT and PESTLE analysis of alternative fuels. *Marine Policy*, 160, 105837. <https://doi.org/10.1016/j.marpol.2024.105837>
- Nag, S., Sharma, P., Gupta, A., and Dhar, A. (2019). Combustion , vibration and noise analysis of hydrogen-diesel dual fuelled engine. *Fuel*, 241(April 2018), 488–494. <https://doi.org/10.1016/j.fuel.2018.12.055>
- Incer-Valverde, J., Korayem, A., Tsatsaronis, G., Morosuk, T. (2023). "Colors" of hydrogen: Definitions and carbon intensity. *Energy conversion and management*, 291, 117294.
- Onorati, Angelo, et al. "The role of hydrogen for future internal combustion engines." *International Journal of Engine Research* 23.4 (2022): 529-540.
- Otomo, J., Koshi, M., Mitsumori, T., and Iwasaki, H. (2017). ScienceDirect Chemical kinetic modeling of ammonia oxidation with improved reaction mechanism for ammonia / air and ammonia / hydrogen / air combustion. *International Journal of Hydrogen Energy*, 43(5), 3004–3014. <https://doi.org/10.1016/j.ijhydene.2017.12.066>
- Pan, H., Pournazeri, S., Princevac, M., Miller, J. W., Mahalingam, S., Khan, M. Y., ... Welch, W. A. (2014). Effect of hydrogen addition on criteria and greenhouse gas emissions for a marine diesel engine. *International Journal of Hydrogen Energy*, 39(21), 11336–11345. <https://doi.org/10.1016/j.ijhydene.2014.05.010>
- Sapra, H., Godjevac, M., De Vos, P., Van Sluijs, W., Linden, Y., and Visser, K. (2020). Hydrogen-natural gas combustion in a marine lean-burn SI engine: A comparative analysis of Seiliger and double Wiebe function-based zero-dimensional modelling. *Energy Conversion and Management*, 207(February), 112494. <https://doi.org/10.1016/j.enconman.2020.112494>
- Saravanan, N., and Nagarajan, G. (2010a). An experimental investigation on hydrogen fuel injection in intake port and manifold with different EGR rates. *International Journal of Energy and Environment*, 1(2), 221–248.
- Saravanan, N., and Nagarajan, G. (2010b). Performance and emission studies on port injection of hydrogen with varied flow rates with Diesel as an ignition source. *Applied Energy*, 87(7), 2218–2229. <https://doi.org/10.1016/j.apenergy.2010.01.014>
- Schuler, J., Ardone, A., Fichtner, W. (2023). A review of shipping cost projections for hydrogen-based energy carriers. *International Journal of Hydrogen Energy*.
- Serrano, J., Jiménez-Espadafor, F. J., and López, A. (2019). Analysis of the effect of different hydrogen/diesel ratios on the performance and emissions of a modified compression ignition engine under dual-fuel mode with water injection. Hydrogen-diesel dual-fuel mode. *Energy*. <https://doi.org/10.1016/j.energy.2019.02.027>
- Shrestha, K. P., Seidel, L., Zeuch, T., and Mauss, F. (2018). Detailed kinetic mechanism for the oxidation of ammonia including the formation and reduction of nitrogen oxides. *Energy and fuels*, 32(10), 10202-10217.
- Solakivi, T., Paimander, A., and Ojala, L. (2022). Cost competitiveness of alternative maritime fuels in the new regulatory framework. *Transportation Research Part D: Transport and Environment*, 113(May), 103500. <https://doi.org/10.1016/j.trd.2022.103500>
- Tsujimura, T., and Suzuki, Y. (2017). The utilization of hydrogen in hydrogen/diesel dual fuel engine. *International Journal of Hydrogen Energy*, 42(19), 14019–14029. <https://doi.org/10.1016/j.ijhydene.2017.01.152>
- Tunestål, P., Christensen, M., Einewall, P., Andersson, T., Johansson, B., and Jönsson, O. (2002). Hydrogen addition for improved lean burn capability of slow and fast burning natural gas combustion chambers. *SAE Technical Papers*, 2002(724). <https://doi.org/10.4271/2002-01-2686>
- Qu, W., Fang, Y., Song, M., Wang, Z., Xia, Y., Lu, Y., & Feng, L. (2024). Hydrogen injection optimization of a low-speed two-stroke marine hydrogen/diesel engine. *Fuel*, 366, 131352.
- Verhelst, S., Demuyne, J., Sierens, R., Scarcelli, R., Matthias, N. S., and Wallner, T. (2013). *Update on the Progress of Hydrogen-Fueled Internal Combustion Engines. Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety*. Elsevier. <https://doi.org/10.1016/B978-0-444-56352-1.00016-7>
- Wang, Y., and Wright, L. A. (2021). A Comparative Review of Alternative Fuels for the Maritime Sector: Economic , Technology , and Policy Challenges for Clean Energy Implementation. *World*, 456–481.

- Xin, G., Ji, C., Wang, S., Meng, H., Chang, K., and Yang, J. (2022). Effect of different volume fractions of ammonia on the combustion and emission characteristics of the hydrogen-fueled engine. *International Journal of Hydrogen Energy*, 47(36), 16297–16308. <https://doi.org/10.1016/j.ijhydene.2022.03.103>
- Xing, H., Stuart, C., Spence, S., and Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *Journal of Cleaner Production*, 297(April 2018), 126651. <https://doi.org/10.1016/j.jclepro.2021.126651>
- Yapicioglu, A., and Dincer, I. (2018). Performance assesment of hydrogen and ammonia combustion with various fuels for power generators. *International Journal of Hydrogen Energy*. <https://doi.org/10.1016/j.ijhydene.2018.08.198>
- Yip, H. L., Srna, A., Yuen, A. C. Y., Kook, S., Taylor, R. A., Yeoh, G. H., ... Chan, Q. N. (2019). A review of hydrogen direct injection for internal combustion engines: Towards carbon-free combustion. *Applied Sciences (Switzerland)*. <https://doi.org/10.3390/app9224842>
- Yousufuddin, S., and Masood, M. (2009). Effect of ignition timing and compression ratio on the performance of a hydrogen-ethanol fuelled engine. *International Journal of Hydrogen Energy*, 34(16), 6945–6950. <https://doi.org/10.1016/j.ijhydene.2009.05.122>
- Zafar, M., Khan, A., Ali, H., Sudarshan, S., Wg, J., and Aziz, M. (2023). Potential of clean liquid fuels in decarbonizing transportation – An overlooked net- zero pathway? *Renewable and Sustainable Energy Reviews*, 183(February), 113483. <https://doi.org/10.1016/j.rser.2023.113483>
- Zareei, J., Haseeb, M., Ghadamkheir, K., and Farkhondeh, S. A. (2020). The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study. *International Journal of Hydrogen Energy*, 45(58), 34241–34253. <https://doi.org/10.1016/j.ijhydene.2020.09.027>
- Zhen, X., Li, X., Wang, Y., Liu, D., and Tian, Z. (2020). Comparative study on combustion and emission characteristics of methanol/hydrogen, ethanol/hydrogen and methane/hydrogen blends in high compression ratio SI engine. *Fuel*. <https://doi.org/10.1016/j.fuel.2020.117193>