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Comparative study on the future of combustion and emissions of internal combustion heavy duty engines with dual-fuel, diesel/hydrogen

Jorge Miguel Lopes Frazão

TRABALHO DE FINAL DE CURSO

Curso: Mestrado em Tecnologias de Valorização Ambiental e Produção de Energia

Docente/Orientador: Prof. Doutor Paulo Brito

Ano Letivo: 2021 | 2023

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"…try humbly to comprehend even an infinitesimal part of the intelligence manifest in nature."

Albert Einstein, *The New York Times, "Materialism Hit by Dr. Millikan," April 30, 1948, p. 21.*

Acknowledgments

I would like to thank my wife, my son and my parents for their continuous support and patience during this (another) stage in my life. To Fravizel S.A. for the support and provision of some instrumentation. To BIOBIP and their team, especially to Luís Calado for his availability during the testing's. I would also like to thank Acail Gas for supplying the gaseous hydrogen with equipment and Professor Paulo Brito for his insights during the development of this work.

Abstract

In this work, a comparative study on the effects of partial replacement of diesel by hydrogen in fuel efficiency, energy substitution, volumetric efficiency and exhaust emissions of a dual fuel engine fueled with diesel/hydrogen was conducted experimentally. The experiments were conducted at fixed speeds of 1000, 1250, 1500, 1750 and 2000 rpm at no load. The hydrogen was injected in admission port alt flows ranging from 1 to 15 l/min. The results indicated that adding hydrogen influenced fuel economy, with savings from 6.2% to 28.2% depending on the engine's rpm. It was also registered an increase in volumetric efficiency of 23.4% with less 50% CO and 83% NOx. Nevertheless, the total energy input decreased 17% at 2000 rpm and 15 l/min of H_2.

Keywords: Dual-Fuel, Hydrogen, Heavy-Duty machinery, Non-Road Mobile Machinery, NRMM, GHG Emissions, Mining, Quarrying.

List of abbreviations, Acronyms and Symbols

A/F Ratio	Air Fuel Ratio
ATDC	After Top Dead Center
B10	10% biodiesel and 90% diesel blended fuel
B100	Pure Biodiesel
B20	20% biodiesel and 80% diesel blended fuel
bcm	Billion Cubic Meter
BEV	Battery Electric Vehicle
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
BTL	Biomass to liquid
CAPEX	Capital Expenditure
CH_4	Methane
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Chloroprene Rubber
CTL	Coal to Liquid
DF	Dual Fuel
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
e-Diesel	Electro-Diesel
e-Fuels	Electro-Fuels

EGR	Exhaust Gas Recirculation
EGR	Exhaust Gas Recirculation
EU	European Union
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
FKM	Fluor Carbon or Fluor Elastomers
FT	Fisher-Tropsch
GHG	Green House Gases
GVW	Gross Vehicle Weight
H2	Hydrogen
HDV	Heavy Duty Vehicles
HVO	Hydro Vegetable Oil
ICE	Internal Combustion Engine
IDI	Indirect Injection
Ktoe	Kilo tonne equivalent
LPG	Light Propane Gas
Mt	Metric ton
N_2	Nitrogen
NBR	Acrylonitrile-Butadiene Rubber
NH3	Ammonia
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxide
NRMM	Non-Road Mobile Machinery
NRMM-CE	Non-Road Mobile Machinery – Construction and mining equipment

O_2	Oxygen
OBD	On board diagnosis tool
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbon
PFI	Port Fuel Injection
PM	Particulate Matter
PVO	Pure Vegetable Oils
RED	Renewable Energy Directive
RME	Rapeseed Oil Methyl Ester
SCR	Selective Catalytic Reactor
SME	Soya Methyl Ester
THC	Total Hydrocarbon
TRL	Technology Readiness Level
UHC	Unburned Hydrocarbons
VTG	Variable Geometry Turbo
XTL	X to Liquid

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INTRODUCTION

Mineral resources extraction (mining or quarrying) and construction are key sectors in today's economies. These sectors use specific mobile equipment tailored to their intrinsic needs. Also, in these sectors the decarbonization must take place to meet GHH emission targets. The European Green Deal aims to achieve climate neutrality by 2050 and a 55% reduction by 2030. The EU total emissions have been decreasing since 1990 (4901 Mt CO_2e) by 32% with reference to 2020 (3354 Mt CO_2e) when the target was 20%, meaning that the measures implemented are being effective. Preliminary estimates, indicate that emissions rebounded in 2021 but remain below pre-COVID-19 levels. The 2021 emissions increase was driven by the recovery from the pandemic and a greater uptake of energy sources with higher emissions in the second half of 2021 [1].

Heavy Duty vehicles (HDV) are partly related with NMRR because some share the same ICE with some modification. HDV are road vehicles used to transport heavy loads or passengers, that include trucks heavier than 3.5 tones (laden) as well as buses and coaches. They are responsible for a quarter of CO_2 emissions from road transport in the EU [2]. HDV have specific emission regulations different from cars and vans. Many Non-Road Mobile Machinery (NMRM) share the same power units of the HDV specially in the small to medium range, meaning that much of the development done in HDV ICE will be also implemented by OEMs in NRMM.

Background and Justification of the Theme

The European Commission has set the target for 55% reduction in emissions for new cars and light commercial vehicles by 2030 and zero emissions by 2035. This objective sends a clear signal to manufacturers and citizens of the need to accelerate the development, production, and sale of low- and zero-emission vehicles. Specifically, for NRMM, stage V engines are already mandatory but at expense of increased prices that probably many industrial users will refrain from buying, keeping older equipment running. Now the energy transition to fossil free fuels raises questions in how the internal combustion engine (ICE) will remain in this transition specially for NRMM, and how will it be possible to adapt and minimize GHG emissions in such equipment's.

General and Specific Objectives

The primary goal of this study is to conduct a comprehensive investigation into the technical obstacles associated with implementing alternative renewable fuels in heavy-duty engines, with a specific focus on Non-Road Mobile Machinery (NRMM).

This research aims to gain insights into the prevailing trends and their effects on dual-fuel combustion, particularly the co-utilization of diesel and hydrogen (Diesel + H_2). The investigation focuses on how this dual-fuel approach impacts the performance of conventional Compression Ignition (CI) engines, which are conventionally powered by fossil diesel fuel and widely employed in industrial machinery.

Methodology and Means Used

In the research methodology and data collection process included thorough exploration of academic article databases, analysis of manufacturers' Original Equipment Manufacturers (OEM) datasheets, examination of commercial materials, and the review of press releases.

For the experimental phase, a Compression Ignition Internal Combustion Engine (CI ICE) equipped with a mechanical injection pump served as the test platform. The fuels utilized for the experiments consisted of diesel fuel compliant with the EN590 standard and high-purity hydrogen gas with a purity level of 99.9999%. These experimental components were instrumental in generating the data necessary for the research investigation.

Research Limitations

This research is limited to NRMM, compression ignition (CI) internal combustion engines (ICE) and the experimental tests were focused on fuel efficiency, volumetric efficiency, and exhaust emissions under. It didn't include dynamometer with controlled load conditions.

Work Structure

The work was divided in two chapters. First chapter is a review on the state of the art in biofuels, CI ICEs and the GHH reduction approaches of the major OEMs. The second chapter is the results of an experimental dual-fuel CI ICE with fossil diesel and H_2.

CHAPTER I – REVIEW ON THE STATE OF THE ART

1.1. European GHG Emissions

In the European Union (EU), Heavy-duty vehicles (trucks, lorries, etc.) are responsible for approximately a quarter of GHG emissions from road transport[3] [4]. Emissions in this sector have increased every year since 2014, dropping only in 2020 because of the COVID-19 pandemic. For trucks, the primary cause of this trend is a growing demand for freight transport. It is partly offset by the improved energy efficiency of road freight transport [4]. To reach the climate neutral goals, a 90% reduction in GHG emissions from transport vehicles will be needed, and every part of the sector will have to contribute to the reduction [4].

1.2. Non-road mobile machinery (NRMM)

The EU regulation 2016/1628 defines 'non-road mobile machinery' (NRMM) as "*means any mobile machine, transportable equipment or vehicle with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on roads*" [5]. The same regulation states that it also lays down certain obligations in relation to NRMM in which an engine as referred to in Article 2 "*is being, or has been, installed, as regards the emission limits for gaseous and particulate pollutants from such engines*". For example, these regulations don't apply to agricultural and forestry tractors, stationary machinery, sea-going vessels, and recreational vehicles. NRMM includes construction equipment, railroad engines, inland waterway vessels, and off-road recreational vehicles.

It also defines which are the pollutant gases emitted from the engine, i.e., carbon monoxide (CO), total hydrocarbons (HC) and nitrogen oxides (NOx); NOx being nitric oxide (NO) and nitrogen dioxide (NO_2), expressed as NO_2 equivalent; 'particulate matter' or 'PM' means the mass of any material in the gas emitted by an engine that is collected on a specified filter medium after diluting the gas with clean filtered air so that the temperature does not exceed 325 K (52 °C); 'particle number' or 'PN' means the number of solid particles emitted by an engine with a diameter greater than 23 nm.

Also, it defines 'dual-fuel engine' meaning an engine that is designed to simultaneously operate with a liquid fuel and a gaseous fuel, both fuels being metered separately, the consumed amount of one of the fuels relative to the other one being able to vary depending on the operation among other technical parameters.

Non-road mobile machinery (NRMM), sub-type construction equipment (NRMM-CE), have some challenges related to decarbonization. Typical these equipment's range from small to very large size with various work cycles from momentary power peaks, continuous max load and intermittent work. Small size machinery work sites are normally close to energy infrastructures and are characterized by low loads, short travel distances and low work time. Some of these challenges are directly related to emissions and the job nature, jobsite conditions, environmental conditions, altitude, machine type and size, engine conditions, idling time control and operator skills.

The Committee for European Construction Equipment (CECE) resumed the existing technologies that have potential towards zero emissions in NRMM-CE: ICE, BEV, FC and off-board power supply plus electric motor [6]. For ICEs, the zero emissions will not be achievable because there will be still some emissions from the burned lubrication oil in the combustion chamber [7]. Small NRMM-CE can be adapted to battery or fuel-cell energy. The same cannot be said for large machinery that usually have work sites with limited access to energy refueling infrastructure and have more harsh work cycles and environments and thus, harder to be electrified unless they are stationary or there is somehow local and decentralized energy production. In this last case where internal combustion engine is a must, the use of biofuels can be a great advantage to contribute to the decarbonization of NRMM-CE while taking advantage of the more than proved technologies of the ICEs.

1.2.1. Regulations & Legislation for NRMM emissions

European directive 2009/30/EC requires non-road Diesel to comply with the same specifications as on-road diesels.

Emissions for NRMM engines started being regulated in European Union countries since 1999 with Stage I standard, when the on-road counter parts started in 1993 with the Euro 1 standard for emissions. Some believe this as lead to a delay in the application of more restrict objectives and it could compromise the reduction of GHG emissions or even to be greater than on-road vehicles at some point in the future. This delay in implementation was alleged on the assumption that the NRMM sector had little impact on the EU GHG emissions [8].

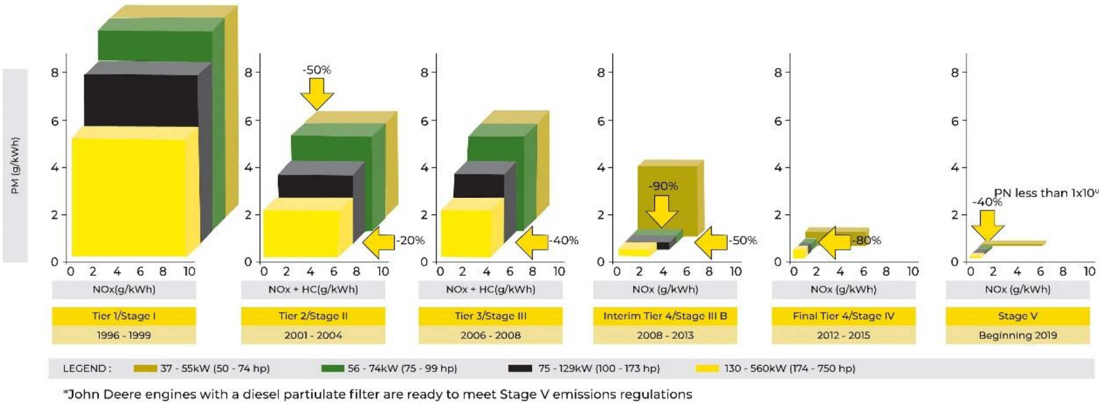
Table 1 – EU NRMM emissions regulation progress

Directive	When adopted	Progress
97/68/EC	1999 to 2002	Established Stage I and Stage II emission standards setting exhaust emission limits for diesel-fueled engines with a horsepower rating between 37 and 560 kW, and emission parameters included HC, CO, and PM.
2002/88/EC	2002 to 2003	Extended the scope of the previous directive to apply Stage I and Stage II emission standards to gasoline engines up to 18 kW. Diesel for 18-560 kW engines. Emission standards for PM and NOX were reduced by 50–60%
2004/26/EC	2006 to 2007	Incorporated Stage IIIA, IIIB, and IV emission standards. This directive also extended the scope of regulated diesel engines to those rated beyond 19 kW and added constant speed engines.
2006/105/EC	November 2006	Introduced modifications to Directive 97/68/EC regarding concerns on the approval certificate numbering system.
2010/26/EU	March 2010	Modified type approval requirements for Stage IIIB and IV emission standards.
2011/88/EU	November 2011	Revised the flexibility percentage for Stage IIIB engines.
2012/46/EU	December 2012	Updated directive 97/68/EC to reflect technical progress on emission measures.
2004/26/EC	2014	Stage IV started being implemented.
2016/1628/EU	2019	Requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines. Stage V started being implemented.

Source: [9] and updated

Emissions from non-road engines (NRE) are regulated by Regulation (EU) 2016/1628 ('NRMM Regulation'), on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for NRMM. This regulation also applies to other category engines excluded from this review (hand-held, inland waterway vessels, locomotives, etc.).

Figure 1 - EPA and EU nonroad emissions regulations: 37-560kW



Source: https://www.deere.asia/en/blog/emissions-regulations-part1/

The following table resumes the regulation for NRE engine category "other NRMM".

Table 2 – Stage V emission limits for engine category NRE

Engine sub-category	Power range kW	Ignition type	CO	HC	NO_x	PM mass	PN	A
			g/kWh	g/kWh	g/kWh	g/kWh	#/kWh	
NRE-v/c-1	0 < P < 8	CI	8.00	($HC + NO_x \leq 7.50$)		0.40 (1)	—	1.10
NRE-v/c-2	8 ≤ P < 19	CI	6.60	($HC + NO_x \leq 7.50$)		0.40	—	1.10
NRE-v/c-3	19 ≤ P < 37	CI	5.00	($HC + NO_x \leq 4.70$)		0.015	1×10^{12}	1.10
NRE-v/c-4	37 ≤ P < 56	CI	5.00	($HC + NO_x \leq 4.70$)		0.015	1×10^{12}	1.10
NRE-v/c-5	56 ≤ P < 130	all	5.00	0.19	0.40	0.015	1×10^{12}	1.10
NRE-v/c-6	130 ≤ P ≤ 560	all	3.50	0.19	0.40	0.015	1×10^{12}	1.10
NRE-v/c-7	P > 560	all	3.50	0.19	3.50	0.045	—	6.00

(1) 0,60 for hand-start, air-cooled direct injection engines

Source: [5] defined in point (1) of Article 4(1) (Table II-1)

The mandatory date of application was January 2019 except NRE-v/c-5 which date was January 2020.

1.2.2. Emissions from NRMM

There aren't many unified data of GHG emissions from NRMM available in EU which in turn makes it difficult to analyze and estimate their emissions. U.S.A. and Switzerland have developed NRMM emission inventories, and several countries are still in the very early stages of their implementation. Additionally, there are very few articles available in the literature [8].

For NRMM-CE, it was assumed that their GHG emissions were not significant [8]. This could explain the gap between road and non-road emission standards. A report from the Swedish Transport Administration [10] declares that NRMM contributes significantly to overall emissions of green-house gases and air pollutants (18% of EU's CO_2 emissions).

One of the reasons arises from a vast range of machine types with an even more range of applications, especially the ones that work with different attachments. As a consequence, a number of different engine types and designs with varying fuel consumption profiles and power outputs, results in a diverse emissions profile [8].

Fan [11] did a critical review and resumed four main factors affecting the emissions of construction equipment: (1) Equipment and conditions, (2) Equipment maintenance, (3) Equipment operations and (4) operating conditions. These main factors are subdivided in several sub-types.

Another reason arises from the difficulty of measuring in real-work conditions. This lack of data and related statistics has also led to inaccuracies in estimating overall emissions and inventories from NRMM [8].

Notter B. [12], made an emissions inventory in Switzerland and concluded that the share of the non-road sector in total mobile energy consumption is 9% in 2015 and that the share in air pollutant emissions is even higher due to the time lag between emission standards and the rejection of older specifications equipment.

DeSouza et al. [13], quantified the 'real-world' tail-pipe NO_X, CO_2, and particle emissions (PM), for 30 of the most commonly used construction machines in London under normal working conditions. The highest NO_X emissions (g/kWh) were from the older engines (Stage III-A ~4.88 g/kWh and III-B ~4.61 g/kWh), these were reduced significantly (~78%) in the newer (Stage IV ~1.05 g/kWh) engines due to more advanced engine management systems and exhaust after treatment. Higher NO_X conformity factors were observed for Stage IV machines, due to the lower NO_X emission standards. On average, Stage III-B machines (~525 g/kWh) emitted the lowest levels of CO_2 emissions, compared to Stage III-A (~875 g/kWh) and Stage IV (~575 g/kWh) machines. Overall, a statistically significant (~41%) decrease was observed in the CO_2 emissions (g/kWh) between Stage III-A and III-B machines, while no statistically significant difference was found between Stage III-B and IV machines. Also, the article resumes some data from the London atmospheric emission inventory 2016, for example, that the total PM2.5 – the 3rd largest source, 34% of the total PM10 – the largest source (includes fugitive dust and diesel exhaust), 7% of the total NO_X – 5th largest source, and 1% of the total CO_2 of emissions.

In the U.S.A., non-road diesel machinery contributed around 11% in total for GHG, 35% NO_X and 40% PM emissions according to statistical data from 2017 (U.S. Environmental Protection Agency in 2017). A U.S.A. Department of Energy report states that off-road vehicles are responsible for 10% for GHG emissions in which construction and mining equipment account for 36% of off-road energy use [14].

Hagan R. et al. [8], made an extensive and comprehensive review of Directive 2016/1828 and collected some data on emissions attributed to off-road sources from the 'EMEP Centre on Emissions Inventories and Projections, 2020' for the EU-27 countries and the UK and concluded that they are significant source of some pollutants because they represented in 2015: 758.6 kilotonnes (kt) of NOx (9.4% of the total 8047.5 kt), 50.2 kt of PM2.5 (3.8% of the total 1321.9 kt) and 29.2 kt of black carbon (13.4% of the total 218.5 kt).

In some EU cities, air-quality regulations at the city level are being implemented and reinforcing decarbonization rules and steering customers to zero-emissions excavators, loaders, graders, and lift trucks [15]. Green public procurement can and will be a way for all stakeholders to achieve zero emissions construction sites[16].

Since the EU is taking the worldwide lead in GHG emissions reduction it should stand out the importance of emissions inventories from all EU countries.

1.3. Alternative Renewable Fuels

The standardization is essential for correct development and operation of the ICE and control of emissions. Since the Diesel cycle is so important in NRMM and the technology is more than validated, current and future biofuels should have similar specifications.

In Europe, RED II directive (2018/2001) was adopted in December 2018 and entered into force on 24 December 2018 was built on the previous renewable energy directive (2009/28/EC) and seeks to further promote the use of renewable energy across the EU. The directive sets a target for the EU to have at least 32% of its final energy consumption coming from renewable sources by 2030. The directive also establishes a framework for promoting the use of renewable energy in heating and cooling, transport, and electricity generation.

The RED II European Directive defines several key elements related to the promotion of renewable energy in the European Union. One of the key elements include biofuels and bioliquids establishing new sustainability criteria for biofuels and bioliquids to ensure that their production does not have negative environmental impacts, including on land use, food security, and biodiversity [17]. This means that sustainability is of most importance and only those fuels that comply with these rules will be able to be distributed and sold commercially in the future[18].

Current fossil Diesel fuel has a specific standard for Europe, the EN590, in U.S.A. the ASTM D975, in Japan the JIS K2204 and China GGB 19147. The EN590 already admits in the composition a maximum of 7% (V/V) Fatty Acid Methyl Ester (FAME). The ASTM D975 has grade 1 and 2 for 7% and 5% (V/V) of biodiesel. The EN16709 standard defines the requirements for diesel fuel containing 14 to 20 vol% (B20) or 24 to 30 vol% (B30) of FAME. The EN14214 standard describes B100, 100% biodiesel. EN 15940 is the standard for paraffinic diesel fuels (ex. HVO) and it also includes GTL (Gas to liquid), BTL (Biomass to liquid) and CTL (Coal to liquid).

Puricelli et al. [3], did a review on the current status and the future perspective of both the commercially available biofuels and the most promising ones under development, with the added value of restricting the scope to Europe, allowing for a more in-depth discussion of markets, regulations and impacts, including quantitative analysis of these topics.

The biofuels can be divided into three or four generations and are resumed in the following table:

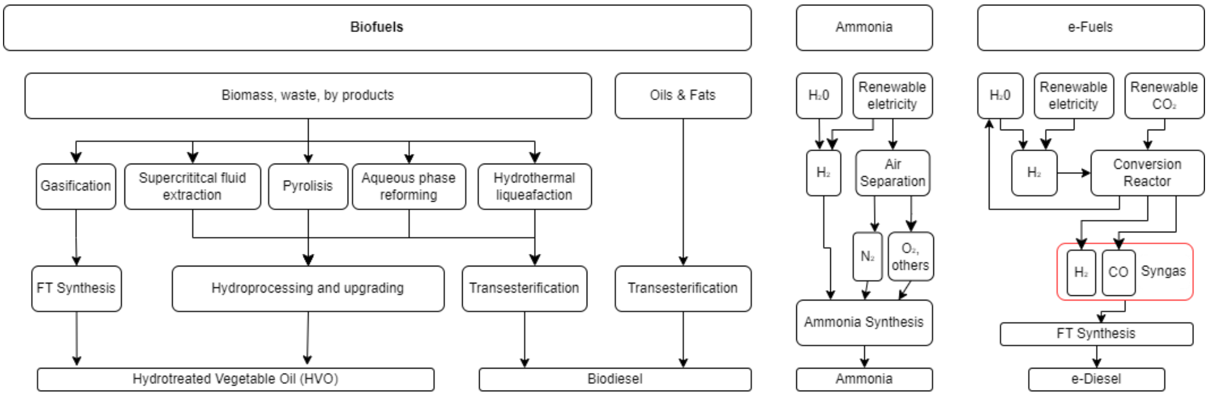
Table 3 – Biofuels by generation

		Origin	TRL	CO_2 Reduction	Disadvantages
First Generation	**Agricultural products**	Food and energy crops (corn, sugarcane, soybean, oil seeds, etc)	High	Up to 50%	The competition with the food supply-chain
Second Generation	**Agricultural waste products**	Non-food and -feed energy crops (e.g., straw, wastes, etc	Medium/ high	Up to 90%	Complexity of processes and the scarce availability of raw materials. Production is more complex and expensive
Third Generation	**Algae**	Algae, microalgae & cyanobacteria	Medium/ high		High cost and low productivity
Fourth Generation	**Genetically modified Microorganisms and photosynthetic micro-organisms**	Thermochemical processes, waste CO_2, etc	Low		Risk of discharge of the genetically modified microalgal strains into surrounding water bodies

Source: Adapted from [3][19][18]

These biofuels can be obtained from several chemical processes. The following table summarizes the processes need to obtain HVO, FAME, Ammonia and e-diesel.

Figure 2 - Simplified overview on how to obtain non-fossil diesel



Source: Own elaboration

Bioenergy Europe 2020 statistics report, states that in 2020 16,323 Ktoe of biofuels were produced representing 90% of the renewable transport mix in which 84% was diesel and 16% ethanol resulting in a save of 34.469 $MtCO_2eq$.

Comparatively to fossil diesel, there are advantages and disadvantages from using biofuels. For example, biodiesel or e-diesel could have the same GHG emissions as fossil diesel depending on the source of carbon but with a better efficiency well-to-wheel.

Efficiency it's very important factor to evaluate a system. The efficiency of a vehicle is measured by the amount of fuel that is converted into useful work. For example, a BEV is very efficient system, 75-85%. Well-to-wheel combines well-to-vehicle and vehicle-to-wheels efficiencies. Well-to-vehicle efficiency takes in consideration all the efficiencies from fuel extraction to storing in a fuel tank of a vehicle. Comparably, Vehicle-to-wheels efficiency is the calculated based on the final use of the fuel on a vehicle, where fuel is processed to provide power to a vehicle.

Table 4 – (Dis)Advantages of zero emissions technologies

	Bio/ synfuel	HVO ICE	Green Ammonia ICE	Green Hydrogen ICE	Hydrogen Fuel Cell	Battery electric
CO_2 Intensity	Lower but depends on feedstock	Lower but depends on feedstock and production process	Very Low with renewable electricity	Zero/minimal if using green/blue H2	Zero/minimal if using green/blue H2	Depends on grid mix. Zero if renewable
Air Quality	NOx and PM identical to fossil diesel	-7 … -14% NOx -28 … -46% PM	Not significant with SCR aftertreatment	Not significant with SCR aftertreatment	Zero emissions while using	Zero emissions while using
Efficiency (well-to-wheel)	≈20%	-40% (Similar to fossil Diesel)	(Similar to fossil Diesel)	≈30% for renewable H_2 production (Compared to fossil Diesel)	≈35% for renewable H_2 production (Compared to fossil Diesel)	75-85% + depending on transmission and charging losses
Powertrain capital expenditure	Same as actual ICE	Same as actual ICE	No significant increase	Same CAPEX as diesel ICE but H_2 requires extra tank	High capex for fuel cell and batteries, but more scalable than BEV	High CAPEX if large batteries required
Constraints (Space/ payload)	Same as actual ICE	Same as actual ICE	Same as actual ICE	Same as actual ICE + H2 tank volume	More space needed	Higher weight, payload constraints
Uptime/ refueling	Same as actual ICE	Same as actual ICE	Same as actual ICE	<15-30 minutes, depending on tank size	<15-30 minutes, depending on tank size	3+hours depending on ability for fast charging
Infrastructure costs	Existing infrastructure	Existing infrastructure	Adaptation in current refueling infrastructure	New infrastructure	New infrastructure	New infrastructure and grid upgrades

BEV - Battery electric vehicle
NOx - Nitrous oxide
SCR - selective catalytic reduction

Source: Adapted from [15][20][21][22][23]

As for Rudolph Diesel, he made the first steps for ICE CI, changing from steam with coal combustion to vegetable oil (1st Mr. Diesel experience), to fossil diesel. Now the energy transition to fossil free fuels raises questions in how the ICE will remain in this transition, and how will regulators see their use in the medium long run since the EU as already decided the 2035 zero emissions targets for new road passenger cars and new light vehicles [24].

1.3.1. Bio-fuels technology readiness level (TRL)

TRL stands for "Technology Readiness Level," and it is a scale used to assess the maturity of a technology or innovation. The TRL scale ranges from 1 to 9, with each level representing a different stage of development. Overall, the TRL scale is a useful tool for assessing the maturity and readiness of a technology for practical application. The current TRL of known biofuels varies depending on the specific type of biofuel and the production technology used. However, many biofuels are already at a relatively high level of TRL, with some already being deployed on a large scale.

For example, biodiesel produced from vegetable oils or animal fats using established technologies is currently at a high TRL, as it has been in commercial use for many years and being integrated into fossil diesel blends. Ethanol produced from sugar crops, such as sugarcane, also has a high TRL and is widely used as a fuel additive.

Other biofuels, such as cellulosic ethanol, which is produced from non-food biomass, and renewable diesel, which is produced from a range of feedstocks including waste oils and fats, are at a lower TRL but are currently being scaled up for commercial deployment.

There are also emerging biofuel technologies, such as algae-based biofuels and synthetic biology-based biofuels, which are at a lower TRL and still in the research and development phase.

Overall, the TRL of known biofuels varies depending on the specific technology used and the feedstock used for production, but many biofuels are already at a high level of TRL and are being used on a large scale.

Table 5 – Biofuels production technology TRL

Biofuel / Technology	TRL
Algal biofuels	2018
Biodiesel (Fame)	First generation: TRL 9 (2020) [66] Second generation: TRL 9 (2020) [66] Third generation: still under development [89,90]
Biohydrogen from: - **woody biomass gasification** - **water electrolysis** - **thermolysis and photolysis** - **biological conversion**	 TRL 7 TRL 9 TRL 1–2 TRL 4–5
Biomethane from biogas	Fully mature technology (2020) [66] TRL 8–9 (2014) [68]
HVO	TRL 9 (2020)

Source: [25] [66] [68] [89,90]

1.3.2. e-Fuels

Fischer-Tropsch (FT) synthesis and conventional petroleum processes are both methods of producing fuels and other hydrocarbon products. However, they differ in several important ways. Firstly, FT synthesis uses a feedstock of carbon monoxide and hydrogen. This means that FT synthesis can be used to produce fuels and other products from a variety of sources, including coal, natural gas, and renewable feedstock such as biomass.

The 'e-fuels' or 'Electro-fuels' can be obtained from renewable CO_2 from different origins (also biogenic origin), renewable electricity and renewable hydrogen from water electrolysis. The renewable CO_2 can be obtained from air capture or other, the H_2 is obtained from the water electrolysis with renewable electricity, following a Reverse-Water-Gas-Shift reactor to obtain a syngas. After that, the syngas is converted in crude oil with a Fischer-Tropsch reactor under the influence of pressure, temperature, and a catalyst (www.norsk-e-fuel.com). Secondly, the products of FT synthesis have a different molecular structure compared to those produced by conventional petroleum processes. FT synthesis tends to produce straight-chain hydrocarbons with little or no branching, while petroleum processes typically produce hydrocarbons with complex, branched structures. This structural difference can affect the properties of the final product, such as its viscosity and boiling point. Thirdly, FT synthesis can produce hydrocarbon products with very low levels of impurities, such as sulfur and nitrogen compounds, which can be harmful to the environment and to human health. This makes FT synthesis an attractive option for producing cleaner fuels [18].

The reaction conditions for FT synthesis are also different, in terms of lower or higher temperatures and pressures typically used. High-Temperature FT synthesis (HTFT) use fluidized bed reactors and circulating catalyst reactors with Iron (Fe) based catalysts, in the temperature range of 300−350°C and a pressure of 2.5−4.5 MPa. HTFT produces mainly light products, gaseous and gasoline fractions. On the other hand, low temperature FT synthesis operates in the temperature range of 200-240ºC and a pressure of 2.5 MPa, using cobalt (Co) (lower water-gas-shift activity) or iron (Fe) (higher water-gas-shift activity) as catalysts, being obtained heavier hydrocarbons, such as waxes, lubricant oils or Diesel, which have high molecular weights and low volatility. One advantage of LTFT synthesis is that it can be carried out using a wider range of feedstocks than high-temperature FT synthesis, including lower-quality feedstocks such as biomass. [18].

According to the EU Directive 2018/2001 (Renewable Energy Sources) renewable (liquid and gaseous transport) fuels of non-biological origin (ReFuNoBIO) refer to fuels used in the transport sector other than biofuels or biogas. If there is a growth in 'electro-fuels' will mean "electrical energy generation capacity will have to be expanded considerably" [26]. The e-fuels produced must be in accordance to the RED II limit of 28,2 gCO2eq/MJ, representing a 70% reduction in GHG compared to fossil diesel, 94 gCO2eq/MJ. [17].

The e-fuels can be used as direct drop in fuel in the ICE due to near Diesel specifications and has positive effects on the environment and society. Its raw materials can be renewable, more environmentally friendly than conventional fossil fuels, being a pure hydrocarbon fuel without sulfur or polyaromatic hydrocarbons. Also, it can meet the sustainability criteria, because it doesn't have the negative effects of biodiesel in the form of FAME. The fuel meets the performance requirements - high cetane number/index, low heat of combustion, high smoke point and small particulate emissions [18].

As an application example, Porsche started the construction of an e-fuel plant in Chile in 2021 together with MAN-ES and plans to build more in Australia and U.S.A., while 'Norsk e-Fuels' plans to start production in 2024 with an expected output of 12,5 Million liters per year.

1.3.3. Biodiesel

Biodiesel is a liquid fuel produced from lipid feedstocks such as vegetable oils or animal fats. Those feedstocks must be subjected to a transesterification process to bring the oil properties closer to those of diesel, resulting in a fatty acid methyl ester (FAME), known as biodiesel [3]. The re-estering of greases or oils (triglyceride) are done with methanol. In Europe biodiesel is usually produced by re-estering of rapeseed oil (rapeseed oil methyl ester = RME). In the USA, biodiesel comes almost exclusively from soya oil (soya methyl ester = SME). Other vegetable oils (sunflower oil, palm oil, jatropha oil), animal fats or used vegetable oils (frying fats) are also possible as raw materials. [27]

Biodiesel is usually blended with conventional diesel on different percentages. Standard EN590 admits 7% FAME. Launched in 2015 the EN16709 "B20" and "B30" diesel fuel standard defines requirements for diesel fuels containing 14.0 to 20.0 vol% (B20) or 24.0 to 30.0 vol% (B30) FAME. B20 and B30 can be used only in dedicated fleets since they do not meet the density requirement of maximum 845 kg/m^3 set by the Fuel Quality Directive 2009/30/EC, Annex II for market fuels. However, B20 and B30 should be manufactured by adding FAME into EN 590 diesel fuel [28].

The EN14214 standard, published in 2008, refers to B100, 100% biodiesel. It applies only to methyl esters, i.e., biodiesel produced using methanol.

Biodiesel has a solvent nature resulting in specific adaptations above B20 blends. Some manufacturers such as Caterpillar already provide such compatibility as standard [29], and as for Deutz, all their diesel engines are approved up to B30 (30%) [30]. Special care must also be addressed because of the more hygroscopic properties of biodiesel that can result in potential condensation on storage tanks and microbial growth. At low temperatures, biodiesel may gel or freeze. Gelling of biodiesel increases with the increase of blend levels and may depend on the biodiesel feedstock [31].

1.3.4. HVO

Hydrotreated Vegetable Oil (HVO) is a mixture of straight-chain and branched paraffins, the simplest form of hydrocarbon molecules under the aspect of clean and complete combustion. Typical carbon numbers are C15 ... C18 [32]. It can also be named '*green diesel*' by producers [3]. The fabrication process is done by hydrogenation (or hydro processing), a process that is already used at petroleum refineries to remove sulfur and other contaminants from crude oil [33].

HVO is a XTL (X to Liquid, a.k.a. Fischer-Tropsch fuels) and falls into EN 15940:2016 standard for paraffinic diesel fuels and it also includes GTL (Gas to liquid), BTL (Biomass to liquid) and CTL (Coal to liquid). In these possible sources are fossil fuels such as GTL or CTL. GTL can be renewable biogas [32]. EN 15940 has two main fuel grades: High cetane class A (min. 70) and normal cetane class B (min. 51) [28].

EN 15940 states "*Paraffinic diesel fuel is not validated for all vehicles, consult vehicle manufacturer before use*". [28] also says that "*even though paraffinic diesel should not cause any risks in engines or vehicles, Euro VI exhaust regulations may formally require that vehicle manufacturers need to give an allowance to use paraffinic diesel*".

They also fulfil the American diesel fuel standard ASTM D975 1-D/2-D – S15 and, apart from the density, the European diesel fuel standard EN 590 as well.

They differ from fossil diesel fuel as follows:

- Chemical composition – Pure paraffin / ISO paraffin – no aromatics – no carbon double bonds.
- High cetane number.
- Positive effects on – Emissions (nitric oxides and particles, CO, HC, PAH, aldehyde and mutagenic emissions) and engine acoustics.
- Reduces cold start smoke and emissions in winter conditions.
- Improved specific fuel consumption in g/kW.h.

- Lower density – Resulting in a lower engine performance.
- Lower lubricity – Very low sulfur content. Needs additives.

The typical feedstock is any vegetable oils or animal fat such as, palm oil, rapeseed, sunflower, soybean, algae oils and used cooking oil. It can as well use oils produced as by-products of various industrial processes such as tall oil (a residue of wood pulp and the paper industry), technical corn oil (oil taken from DDGs, the co-product of grain ethanol plants), palm oil effluent, palm fatty acid distillate, pyrolysis and hydrothermal based oils. For the process a multistep hydrotreating of the feedstock with hydrogen is used. Today hydrogen is sourced from natural gas steam reforming or internal naphtha reforming. The challenge of this process, for 100% renewable HVO is the source of renewable hydrogen. Compared to biodiesel, HVO has higher quality, higher cetane and no aromatics resulting in better combustion. The downturn is the availability of common feedstock and the impact on indirect land use and usage more linked to palm oil and the lower density that limits higher blends with conventional diesel [34] [28].

In 2018, HVO production in Europe was 2,2 million tonnes with an estimated capacity of 3,9 million tonnes. [35]

HVO might have compatibility issues with NBR polymer seal in specific situations. It has been reported that in older engines that operated for a long time with conventional fossil diesel and then changed to HVO, may occur the swelling of the NBR sealings causing leaks. This is due the freedom of aromatics in paraffinic diesel fuel compared to conventional diesel. But this swelling does not occur if an engine is operated with paraffinic diesel fuel from the start or if the seals and hoses are from FKM. It's recommended to check leaks after a month when an engines fuel is changed from fossil diesel to paraffinic diesel and change seals if necessary [27] (Table 6 – Chemical compatibility chart).

1.3.5. Bioethanol

Bioethanol is a liquid alcohol produced from the fermentation of carbohydrates followed by extractive distillation or membrane separation to obtain anhydrous ethanol. Bioethanol is classified in three generations based on the feedstock used and is blended with petrol in spark-ignition engines. In Europe, for conventional vehicles, the percentage of ethanol blended with petrol is limited to 10%$_{v/v}$ (E10). Flexible fuel vehicles (FFVs), which account for 0.1% of the EU passenger car fleet, can run with a percentage of blended ethanol up to 85%$_{v/v}$ (E85) [3]. In Brazil it's common to have road vehicles with E85 blended gasoline (85% ethanol).

Bioethanol can also be binary or ternary blended with diesel and biodiesel. Only alcohol-diesel emulsions and blends are compatible with most commercial diesel engines. There are no standards on these blends but regular diesel can be typically blended with up 15% (dieselnet.com) [36]. In these blends there is typically an increase in the cumulative heat release, fuel consumption (lower heating value) and NOx emissions (higher combustion temperature) due to the lower heating value while the brake thermal efficiency does not decrease, and the particle emissions and smoke are reduced with the increase of ethanol and biodiesel percentage. There is also a longer ignition delay caused by the ethanol higher autoignition temperature, lower cetane number and higher heat of vaporization, because the blended fuels need more time for fuel evaporation [36].

1.3.6. Biogas, Biomethane and Biopropane

Biogas can be produced by anaerobic digestion from organic wastes and residues, such as agricultural residues (such as manures and straw), or plant materials, municipal or industrial organic waste and wastewater, industry residues (such as stillage). Specially for wet residues in open slurry tanks (manure and pig sludge), anaerobic digestion can be an important process in the production of biogas because it reduces the fugitive GHG emissions. Biogas is a mixture of 60 % methane (CH_4), 40% CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment. The precise composition of biogas depends on the type of feedstock and the production pathway [37]. Biomethane is also known as "renewable natural gas" is a near-pure source of methane (>97%) produced either by "upgrading" biogas (a process that removes any CO_2 and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation [37] [3]. Bio propane/Bio-LPG: can be produced with a one-stage catalytic synthesis of the syngas resulting from biomass gasification, and also as a coproduct of HVO, Higher alcohols and Mixed alcohols [3]. Biomethane can be used in ICEs running on compressed natural gas (CNG). For example, Volvo trucks has commercially available road trucks win CNG with a small fraction of diesel for pilot ignition (dual fuel engine). These engines and surrounding technologies can be easily adapted into NRMM-CE.

Combined biomethane and biogas production in 2021 in Europe reached a total of 18,4 bcm divided into 14,9 bcm from biogas and 3,5 from bcm biomethane. Since 2011, compared to 2021, the production of biogas increased from 6 bcm to 14,9 bcm and biomethane from 0,5 to 3,5 bcm. The biogas production was constant between 2016 and 2021 while biomethane increased. Most biomethane is produced in Denmark and Sweden while biogas is most produced in Slovakia, Germany, Czech Republic, Denmark, Sweden, Switzerland, Finland. [38]

1.3.7. Pure Vegetable Oils

Pure vegetable oils (PVO) are not classified as biodiesel and can be obtained from rapeseed (rapeseed methyl ester RME), soya (Soy Methyl Ester SME or SOME) and palm. It can be used in ICE under certain working condition and technical engine adjustments because PVO has problematic properties if applied in standard diesel engines including great tendency for coking, danger of piston seizure, extremely high viscosity and poor evaporation behavior. In industrial applications, Deutz has approved engines for rapeseed oil (RME, rapeseed methyl ester) that can also run on biodiesel only mode and operating limitations including: Can´t work under 5ºC; should be avoided down time above 4 weeks otherwise engine should be started with diesel fuel; halved oil change intervals; no mixture with other PVOs and the use of fuel additives. Due to lower heating, compared to EN590 diesel, it's expected to have a power loss of 5-10% and extra fuel consumption of 4-5% [27]

1.3.8. Green Hydrogen

Green Hydrogen can be fully renewable and carbon free if obtained from renewable electricity and water electrolysis. Bio-Hydrogen is not considered a biofuel but can be used as energy in a dual fuel or 100% fuel in ICE. Hydrogen can also be used as feedstock for other fuels based on hydrogen such as ammonia, methane, methanol or

Fischer-Tropsch fuels (e-fuels), synthetic kerosene, gasoline or diesel. Using these fuels as energy carriers, has the advantage of being easier to transport and store compared with hydrogen [39].

At present time, there is no market for green Hydrogen, but EU objectives include it for the decarbonization of transport sector. The EU hydrogen strategy plans to ramp-up renewable hydrogen production via electrolysis to 10 million tonnes of hydrogen by 2030, with an installed capacity of 40 gigawatt (GW) electrolyzers [40]. The European Commission recently indicated that our target should be €1.8/kg by 2030, while in 2020, the cost of hydrogen produced through water electrolysis powered by renewable electricity was estimated to be €6/kg [21].

Hydrogen has a high specific energy density and can provide nearly three times as much energy by mass compared with other fossil fuels. The disadvantages are related to storage. Hydrogen has a very low density which in turns correspond to a lower volumetric energy content (MJ/m^3).

Green Hydrogen is mainly obtained from water electrolysis, biomass gasification or microbial electrolysis cells. Water electrolysis could be the leading technology used in the medium and long-term. In scenarios with highly restrictive carbon footprint limits, biomass gasification is apparently an interesting hydrogen production technology in the long-term [41]. Biomass gasification is a thermochemical process without combustion under sub stoichiometric conditions producing H_2, CO, CO_2, CH_4 and N_2. Air can be used as a gasification agent but to increase the H_2 output, other gases can be used, namely O_2, steam, or a combination of them [3].

[39] resuming other articles, reports that commodities with high energy efficiencies and low production costs are LH_2 (52-60%, 149 $/MWh) and ammonia (48-52%, 146 $/MWh), while all other commodities are more costly in production and have a lower energy efficiency. Transport cost to central Europe would range from 1,8-4,30 $\$/Kg_{H2}$ liquified and 0,56$\$/Kg_{H2}$ as ammonia. Also, pure hydrogen has the lowest production costs while having the highest transport costs, especially in maritime transport, concluding that hydrogen will be traded in pipelines within Europe and North Africa. In sea freight hydrogen will be transported via an energy carrier such as ammonia. To

retrieve H_2 from NH_3 the process of ammonia cracking recovers 0,78 kWh H2/kWh NH_3.

1.3.8.1. Hydrogen in ICE

The use of hydrogen as a combustion fuel has the potential to make many heavy-duty and NRMM applications climate-neutral more quickly by adapting current ICEs [42].

Hydrogen properties are interesting regarding thermodynamics. Having high flame speed, wide flammability range and low ignition energy is positive for a good combustion. The wider range of flammability also offers the possibility to operate the engine with ultra-lean combustion thus reducing the NOx emission to a very low level [7] but reducing engine efficiency [43] .

Hydrogen can be used in dual fuel ICE configurations. With Diesel as a pilot fuel with DI and hydrogen in PFI.

Hydrogen combustion in ICE have specific challenges related to higher combustion temperatures resulting in increased NOx emissions. Also, due to his high auto-ignition temperature and higher-octane number, the resistance of hydrogen to knocking is expected to be high. However, with lower minimum ignition energy suggests that hydrogen can be easily ignited by hot spots or residues in combustion chamber leading to pre-ignition of fuel [44].

Any of these systems must be complemented by a suitable exhaust aftertreatment such as a selective catalytic reactor (SCR).

1.3.8.2. Hydrogen Storage

Hydrogen having a low density, has a low volumetric energy content of 10,7 MJ/m^3 compared to $35x10^3$ MJ/m^3 for Diesel [44]. For mobile equipment applications this means hydrogen must be highly compressed up to 700 bar and still will occupy 4,3 times more space compared to conventional diesel tank. Even on dual fuel applications with 50% Diesel and 50% hydrogen, the space needed will 2,6 greater [7]. This causes great constraints on the application of hydrogen as fuel in mobile equipment that already have limited space.

1.3.9. Green Ammonia

Ammonia (NH_3) has one nitrogen atom and three hydrogen atoms. Being the only fuel without a carbon molecule, it's considered a versatile and important carbon-free alternative being also a high-volume chemical produced worldwide [21] with readily available technology. As a liquid it doesn't have color and has sharp smell of gas. This is an advantage with respect to its toxicity because, in a leak occurs, it can be easily identified at about 5 ppm, being the safety levels between 25 and 35 ppm [21].

In the future carbon neutral society, Ammonia can be used as a hydrogen carrier because it's safer to transport than hydrogen having regular requirements as other fuels. Also, when liquefied, it contains approximately 48% more H_2 by volume than H_2 itself. It also has 17,3% hydrogen by mass, higher than Methanol (12,5%), Ethanol (13%), Gasoline (15,8%) and Diesel (13%). Furthermore, ammonia production has a well-established production chain. [45][46].

1.3.9.1. Green Ammonia Production

Green ammonia is produced by using renewable energy sources, such as wind or solar power, to produce hydrogen through the process of electrolysis and nitrogen from the process of separation from atmospheric air [47]. Industrially it can be produced from two different processes, Haber–Bosch and electrochemical ammonia synthesis. Overall, while both the Haber-Bosch process and electrochemical ammonia synthesis are methods for producing ammonia, they are different processes with different inputs and outcomes [21].

The Haber-Bosch process was developed by the German chemist Fritz Haber in the early 20th century and is widely used to produce ammonia as a fertilizer and chemical feedstock. In the Haber-Bosch process, green hydrogen and green nitrogen are reacted together at high temperatures and pressures to produce ammonia. This process is typically carried out using a catalyst, such as iron, to speed up the reaction. It's a very unstable process [21].

The electrochemical green ammonia synthesis is still in an early stage of development and consists of electrochemical N_2 reduction reaction at atmospheric temperature and pressure with green hydrogen. Having a low TRL there are some technologic barriers to overcome due to low rates of ammonia production and process durability related to catalyst degradation. Other routes are being studied such as electrochemical synthesis from nitric oxide, electrochemical production through photoelectrochemically produced hydrogen under concentrated sunlight, photo-electrochemical synthesis, ammonia synthesis using nitrogenase organisms and biomimetic catalysts to create a biotechnological route, and electromagnetic-induced ammonia synthesis [21].

Green ammonia production cost in Germany is 20-80% higher than grey ammonia, depending on the country of origin of raw materials.

1.3.9.2. Ammonia as a fuel in ICE

Ammonia combustion in internal combustion engines is an area of active research and development due to its potential as a clean and renewable fuel for the reason that there are no carbon dioxide emissions and it can be adapted to existing engines with low modifications [47].

Even though great attention from the scientific community and industry, practical applications on internal combustion engines fueled with ammonia are still limited. The recent interest in ammonia as fuel is mainly pushed by the marine shipping industry, which prominently runs with compression-ignition large-bore engines [21]. MAN Energy Solutions is working on a two-stroke ammonia marine application ICE [48].

Ammonia, due to its high-octane number (>130) [45] might need engine modifications (***Table 8 – Biofuels characteristics compared to fossil DieselTable 8***) towards lean combustion, as bigger air compression systems to increase air/fuel ratio and minimizing ignition problems, helping the combustion and contributing also to lower NOx emissions. Also there are recommendations for preheating the ammonia before injection because it helps improving ignition and reaching higher combustion temperature [47].

1.3.9.3. Spark Ignition

In reality, Ammonia can only be used in spark ignition engines using a PFI system in liquid phase or with DI because of its ignition resistivity and low flame speed [49]. The spark timing needs adjustment because ammonia burns five times slower than gasoline[47] but can be explored from the higher octane number [21]. The percentage of replaced gasoline results in the same percentage of decreases CO2 emissions [47].

1.3.9.4. Compression Ignition

Using ammonia as a single fuel in a CI-engine requires high compression ratios to achieve better ignition and efficiency [47][46][45].

Ammonia combustion can be improved in a Dual Fuel engine mode where ammonia is premixed with the air with PFI system, and another fuel is injected directly into the ICE to promote ammonia/air mixture ignition. In dilute mixture conditions, typical of compression-ignition engines, premixed flame propagation is penalized, worsening the combustion efficiency. Replacing 3%v of intake air with carbon-free NH_3 or H_2 allows reducing diesel amount by about 15% with benefits on CO_2 emission up to about 12% [47] [21].

1.3.9.5. Disadvantages

The state of the art in ammonia combustion in internal combustion engines involves several challenges.

High ignition temperature, low flame velocity, low chemical kinetics and less power produced in the ICE. Also, ammonia needs specifically developed injectors to prevent that unreacted ammonia passing through the SCR untreated [47].

Ignition delay: Ammonia has a relatively long ignition delay compared to conventional fuels such as gasoline and diesel, making it challenging to ignite in an internal combustion engine.

Flame stability: Ammonia has a lower flame speed compared to conventional fuels, making it difficult to maintain stable combustion in an internal combustion engine.

Another problem is the NOx emissions when using pure ammonia or ammonia-fuel blends, especially ammonia-hydrogen. This problem can be minimized by applying ammonia oxidation catalyst and catalytic reduction.

Due to its highly hygroscopic characteristic, that causes the formation of moistures, it is possibly very corrosive on metals, especially on copper and brass, commonly used in ICEs as gaskets [21].

Despite these challenges, recent advances in engine technology and fuel injection systems have led to significant improvements in the performance of ammonia-fueled engines. For example, researchers have developed new engine designs that can better control the combustion process, resulting in improved ignition and flame stability. In addition, researchers are exploring the use of catalysts and other technologies to reduce NOx emissions from ammonia combustion.

Overall, the state of the art in ammonia combustion in internal combustion engines is still in the early stages of development, but there is a growing body of research that suggests that ammonia has the potential to be a promising alternative fuel for internal combustion engines in the future specially in Marine sector.

1.3.9.6. Biofuels chemical compatibility with seals

Biofuels, being from organic sources, may be subject to decay or chemical reaction resulting in lower fuel quality, lower shelf time and fuel degradation. Some factors that can accelerate the degradation are elevated temperature, irradiation, oxygen or oxidizing agents and catalytically active trace metals [34]. Standard EN590, for fossil diesel, that can have up to 7% FAME, strongly recommends addition of oxidation stabilizers in the FAME production and storage stage. This is essential to keep the required fuel blend stability, otherwise may cause severe issues in fuel systems components.

For biodiesel, fuel-water separators must be implemented, and compatibility must be checked with manufacturers. Since biodiesel can loosen deposits in tanks, pipes and plugs, fuel filters must be replaced more frequently when changing ICEs fuel source from fossil diesel to biodiesel fuel blends until deposits are fully removed. It is also recommended periodic condition checks of gaskets, seals and hoses because of the risk of degradation that increases with higher blends. Also, since biodiesel increases dilution of engine oil, the change intervals must be reevaluated [31].

Table 6 – Chemical compatibility chart

	Designation	Acrylonitrile-Butadiene Rubber	Fluor Carbon or Fluor elastomers	Chloroprene Rubber
	ISO1629	NBR	FKM	CR
	Mostly known as	Nitrile	Viton	Neoprene
Fuel	**HVO**	A	A	NA
	Biodiesel	C	A	C
	B10	B	A	NA
	Hydrogen	A	A	A
	Ammonia	B	C	A
	Bioethanol	C	C	A
	Methanol	A	C	A
	Biogas	D	D	D
	Biomethane	A	A	B

A- Satisfactory, B- Fair, C- Not Recommended, D- Unknown

[1] Not recommended if engine was previously running on fossil diesel [27]

Source: [27] [28] [29] [50] [51]

1.4. Biofuels comparative

Table 7 - Biofuels comparation

	Fuel	Diesel	Synthetic e-Diesel	Biodiesel B100 FAME	HVO	Gaseous hydrogen	Ammonia
	Standard	EN 590	Fisher-Tropsch	EN 14214	EN 15940		
Chemical Structure (approx.)		$C_{12}H_{23}$	$C_{16.89}H_{35.77}$	$CH_3(CH_2)$ $nCOOCH_3$	$C_{13}H_{28}$	H_2	NH_3
Lower heating value	MJ/kg	43	43.9	38	44	120.1	18.8
Density @ 15 ⁰C	kg/m³	838.8	784.6	860 to 900	780	17.5	602.8
Kinematic viscosity 40 ⁰C	mm²/s	2 – 4.5	2-2.5	3.5 – 5	2 – 4.5	121	16.21
Lubricity at 60 ⁰C	µm	460	430 – 560	190 – 233	344	*NAGM**	*NAGM**
Flammability limits, gas in air	Vol. %	0.6 – 5.5	NA	NA	NA	*NAGM**	16.25
Stochiometric air requirement		14.7	14.91	11.77 – 13.8	14.9 – 15.8	34.1	6.05
Flame speed	m/s	0.87	NA	NA	NA	1.8 – 2.8	0.15
Self-ignition temperature	⁰C	230	NA	NA	>204	571	651
Minimum ignition energy	MJ	0.24	NA	NA	NA	0.018	8
Octane		N/A	NA	x	0	>130	110
Cetane		51	89	51 – 55.2	74.5 – 6.3	NA	0
Storage method		Liquid	Liquid	Liquid	Liquid	Compressed gas	Compressed gas to liquid
Storage temperature	⁰C	25	25	25	25	25	25
Storage pressure	kPa	101.3	101.3	101.4	101.5	24 821	1030
Storage stability		Good	Good	Very challenging	Good	Very challenging	Very challenging
Flash point	∘ C	> 55	NA	101	60.5 to 66.3	*NAGM**	132
GHG	(gCO2 eq)/MJ	94	5.5	26.51	16.75	28	No direct effect

* *NAGM* – Not applicable to gas and mixtures **Source**: [7],[18],[20],[45],[52],[53],[54],[55],[56],[57],[58],[59],[60],[61],[62], [63]

Table 8 – Biofuels characteristics compared to fossil Diesel

	Fuel	Synthetic e- Diesel	Biodiesel B100 (FAME)	HVO	Gaseous hydrogen	Ammonia
	Standard	Fisher-Tropsch	EN 14214 ASTM D6751	EN 15940		
Lower Heating Value	MJ/Kg	2%	-12%	2%	179%	-56%
Density @ 15 ºC	Kg/m3	-6%	3%	-7%	-98%	-28%
Kinematic viscosity 40 ºC	mm2/s	-44% – 0%	10 – 43%	0%		
Lubricity at 60 ºC	um	-7% – 18%	-49%	-25%		
Cetane number		57%	0%	-50%		
Emissions	(gCO2 eq)/MJ	-94%	-72%	-82%	-70%	

1.5. Internal Combustion Engine Systems

The internal combustion engine (ICE), Diesel cycle, goes back to the 1890's when Rudolph Diesel, mechanical engineer, started exploring the result of oil being injected and burned with oxygen, resulting in a patent in 1893 after realizing that the patent of 1892 was wrong. He could not imagine that is invention would revolutionize in such great extend the industrial world with a new technology at that time with more efficiency than steam. This ICE has suffered great extent of development being now the backbone of every industrial NRMM. With the increasing more stringent regulations the NRMM faces the challenge of the decarbonization targets.

There are several technologies used in the Diesel compression ignition (CI) ICE. These different technologies are related to the fuel injection approach.

Port-Fuel Injection (PFI)

PFI it's mostly used in gasoline ICE in which the fuel is injected in the admission port near the admission valve. It is also used in dual fuel ICEs to inject a second fuel.

With PFI of hydrogen , there is always a chance of back-fire and engine knocking at high load [58].

Indirect Injection Combustion Systems (IDI)

Indirect injection systems are only found in diesel ICE and uses a pre-combustion chamber where the fuel in injected. This prechamber is in the cylinder head and it's connected to the combustion chamber. Fuel is injected into the pre-combustion chamber during late compression stroke when air is compressed and being very hot, creating a uniform fuel mixture, followed by the combustion that spreads to main combustion chamber followed by the expansion stroke [64].

Direct Injection Combustion Systems (DI)

The CI DI diesel ICE is the most common injection systems on new ICEs on the market characterized by a high-pressure common rail injection. The fuel is injected directly into the combustion chamber.

DI hydrogen ICE is more complex for the reason that it needs spark ignition, throttle body and it's challenging regarding the combustion stability [7]. Shinde et al. [58] did an outlook on the development of DI of hydrogen, concluding that further research should continue to use late injection strategy to perform near to ideal combustion. The efficiency losses such as compression work, improper combustion and heat transfer to the coolant should be reduced [58].

Table 9 – Direct Injection compared to Indirect Injection

NOx	Higher
CO_2	Higher
CO	Similar
Fuel Consumption	Lower

Source: [64]

1.5.1. Dual Fuel (DF)

One way to mitigate emissions, and since fossil fuels are also finite, using dual fuel ICE can help in the transition for renewable fuels and to increase the efficiency in ICE. Several studies indicate that biofuels are effective alternative fuels for reducing NOx emissions, GHG, and PM [65]. Having two different fuels increases the technical challenges in a DF system because it's required to have a specific fuel system for each fuel, from the tank all the way to the fuel injector. The complexity further increases with the need for an exhaust after-treatment system to manage the diesel specific emissions [7].

Depending on the approach, DF engines can use combinations of several fuels, for instance fossil diesel (or e-diesel, biodiesel or HVO) with hydrogen, biogas, biomethane or others.

In dual fuel engine the main fuel is injected and mixed with intake air by a PFI system and ignited by a small quantity of pilot fuel, i.e., diesel. The first dual fuel injector with concentric needles was developed by Westport based on P. Oullette work started in the 1990s. In the literature there are not many CFD simulations on high pressure dual fuel injection in high speed medium sized engines [66] but there are already solutions in the market.

1.5.2. Dual Fuel with PFI + DI

Dual-Fuel (DF) configuration with PFI and DI can be used for the DF hydrogen and ammonia engines which enables the ignition of the hydrogen by means of a compression ignited pilot fuel [47]. This technology erases the need for a spark plug, simplifying the cylinder head and reducing maintenance. When using pilot ignition, the pilot fuel provides part of the energy. Combining hydrogen with diesel increases the overall energy density of the system compared to hydrogen. [47]

In Ammonia-Diesel DF, it's required a comprehensive blender design and automatic control system to adjust the optimum mixing ratio for ammonia, fuel, and air. For each type of fuel, the blending design and fuel flow rates should be adjusted. With the increase of ammonia blend relative to Diesel, it's expected that output power decreases, being lower than Hydrogen blend, decreasing exhaust temperature with greater variation in the Hydrogen-Diesel blend [47].

The DF hydrogen system reduces the emissions compared to a traditional diesel engine thanks to the hydrogen while keeping a good energy density compared to hydrogen. However, other fuels such as HVO can even reduce emissions compared to the hydrogen engine. This obviously requires fuel to be available, but the DF engine presents itself as a flexible solution that has good low emission potential.

1.5.3. Dual Fuel Injector

Some manufacturers have developed dual fuel injectors. Woordward Inc. (woodward.com) has developed a high-pressure dual fuel injector capable of working with diesel, methane, LPG, methanol and ammonia by varying the injected quantity according to the calorific value of the fuel. The injector nozzle has three concentric gas needles and one central diesel needle [67]. The gas injector system withstands up to 600 bar and diesel system up to 2000bar. Westport along with BorgWagner developed the HPDI^{tm} system for CNG and H2 dual injection with diesel. The CNG system is already used in Volvo road trucks. Westport states that the target is to use the same injector hardware in both CNG and H_2. For H_2, at 50% load Westport states to reach stoichiometric fully ignited H_2 at 8^o ATDC.

Figure 3 - Westport HPDI Injector

1.5.4. Prechamber ignition/combustion

Lean or ultra-lean air-fuel ratios has been used to reduce fuel consumption and pollutant emissions. For example, in hydrogen combustion, challenges arise from engine knocking and premature ignition without reducing compression ratio and consequently efficiency. This can be tackled by operating the ICE with a large amount of excess air. This strategy improves engine thermal efficiency by enhancing combustion quality, by enhancing the in-cylinder turbulence and generating multiple ignition sites reducing heat transfer losses, and allowing for higher compression ratios [68][69]. However, a lower fuel concentration in the cylinder can make it difficult to ignite the mixture, which requires more energy to start combustion where even the energy from a conventional spark plug is not enough to ignite such a mixture [42]. To address this challenge, various high energy provider methods have been studied, including prechamber ignition systems. This system has shown potential in reducing emission levels and fuel consumption while operating with lean burn mixtures and providing significant combustion stability [70]. Typically, the main fuel is injected by PFI or DI and pilot fuel is injected in the prechamber.

Prechamber combustion is a type of combustion system used in some internal combustion engines. It involves the use of a small chamber, called a prechamber, which is separated from the main combustion chamber by a neckline, contains a spark plug and fuel injector. In the prechamber a small amount of fuel-air mixture, is ignited by the spark plug and the resulting flame front then propagates into the main combustion chamber, igniting the air-fuel mixture there. An important benefit of this approach is that a higher power density is achievable and a higher compression ratio can be used compared to premixed approaches, Also, this solution allows for a ultra-lean mixture with an excess air ratio above 3 in the main combustion chamber [68].

MAHLE-powertrains has developed for gasoline engines the Jet Ignition® which replaces the standard spark plug in SI engines with a jet ignition pre-chamber assembly, without requiring a separate ignitor within the main combustion chamber. They supported Liebherr in the development of the engine H966 and H964 for hydrogen. In the Jet Ignition® the prechamber is connected to the main chamber by a number of small orifices where due to its high energy content, rapidly and evenly ignites the main gas mixture[42]. Jędrzej Matla [68] proposes to improve the combustion parameters of the hydrogen-air mixture in the area of light knock. Light knock occurs bellow the heavy knock limit and is caused by the unstable combustion process and is also an undesirable phenomenon, despite its less destructive effect on engine components than in the case of heavy knock. As a result of the vibrations of the piston rings, it can cause their accelerated wear. To improve the combustion process in this area by having a prechamber integrated with the head instead of a small threaded one into the head. This should enable the use of a greater degree of mixture depletion. This solution should ensure better heat transmission from the combustion process and allow for even flame propagation due to orifices installed in the prechamber necking area. The main advantage of the system should be a higher compression ratio while maintaining pressure pulsation below the light knock limit.

Figure 4 - Mahle Jet Ignition

Source: Mahle

1.5.5. Solutions for emissions reductions

1.5.5.1. Post Injection

The post-injected fuel further cracked into small molecular hydrocarbons, then discharged from the cylinder and oxidized by Diesel Oxidation Catalyst (DOC) to release high temperature for Diesel Particulate Filter (DPF) regeneration. This post-injected fuel can also improve combustion by oxidizing the previously generated soot, NOx, and reducing PM emissions. Recent research studies showed that post-injection could improve the combustion phenomenon, bringing about better thermal efficiency, reduction in UHC, PM, and CO emissions can be achieved; however, some research studies also report an increase in NOx. Post-injection close to the main injection can aid in soot oxidation, while a delay in post-injection assists in recovering DPF and cracked into light HC, which aid in the after-treatment devices. [71]

1.5.5.2. NOx mitigation

The more stringent emissions regulations have increased the pressure on manufacturers to better control the NOx emissions in ICE. NOx refers to nitrogen oxides (NO, N_2O, NO_2). NOx occurs in ICE from the high combustion temperatures that oxidizes the nitrogen in air that occurs for example in hydrogen and ammonia ICEs.

The combustion of diesel($C_{12}H_{23}$) with atmospheric air (O_2 and N_2) can be resumed in the following simplified equation:

$$4C_{12}H_{23} + 71O_2 \rightarrow 48CO_2 + 46H_2O$$

This simplified equation represents the combustion of diesel fuel with O_2 and the N_2 in atmospheric air, but the combustion process involves other intermediate reactions and byproducts such as CO, NOx, and PM, depending on fuel composition, combustion temperatures and A/F ratio.

In H_2 combustion the simplified equation for hydrogen combustion in a pure O_2 atmosphere can be written has:

$$H_2 + O_2 \rightarrow CO_2 + 2H_2O$$

This means the combustion of H_2 in atmospheric air produces water vapor as the primary product. N_2 is considered a stable molecule but due when subjected to high temperature can be transformed into NOx above 750 ºC [43]. H_2 high temperature flame can represent problems in the combustion process by creating large amounts of NOx emissions when temperatures rise to 1600K (≅ 1300 ºC) or above [72].

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

Two main approaches can be used to control the NOx emissions, first is ultra-lean combustion and second, posttreatment EGR or SCR. Ultra-lean combustion operation requires several modifications to the engine architecture such as air and fuel path configuration. Operating at a A/F ratio above 2 is slightly more efficient than EGR systems. Ultra-lean conditions can be achieved with multi-stage charging systems with turbochargers, electric or mechanical compressors with inter-stage cooling and controlled by waste-gate and/or VTG turbine. The leaner combustion will result in lower exhaust gases temperatures, lower NOx, but also lower power on turbochargers that need additional support from another compressor/turbocharger. Since air mass flow is higher, engines need a wider and better controllable management map to match performances in steady and transient state. EGR systems can use conventional single stage variable turbine turbocharger [7] [30]. With EGR some exhaust gas is cooled and added back into the combustion chamber. Having less oxygen, because some has been consumed by previous combustion, the recirculated exhaust gas will not increase the combustion temperature.

The choice between both systems depends on the time to market and the level of re-usable components from existing engine platforms. For example, Deutz decided to develop a H_2 ICE (model TCG7.8H2) from an existing platform adapting PFI and changing the diesel injector to a spark plug. According to them fuel- air-exhaust gas mixture, the ignition angle, throttle valve, EGR adjuster and wastegate adjuster all need to be simultaneously adjusted to the most efficient setting for dynamic operation. They've concluded that H_2 combustion has quick reaction to load changes by rapidly adjusting A/F ratio. Nevertheless, with increased mixture enrichment, higher NOx was observed. This means that with proper engine management, it is possible to map the engine to work in the areas with less NOx emissions by adjusting A/F ratio vs rpm even if it means taking longer time to get to max torque (extra 1,5s) with a peak efficiency of 39% and 1,5g/kW.h of NOx that will be near zero with a aftertreatment system [30].

Main downside for ultra-lean combustion is its complexity. The need of two turbochargers and one interstage-cooler results in a less compact engine. The single stage with EGR configuration is more compact and can be a good alternative for NOx emission control. The risk of water condensation and the operation of the EGR valve in the transient phase are the main challenges of the system [30].

As stated, NOx can be reduced with post treatment technologies, Exhaust Gas Recirculating (EGR), Selective Catalytic Reduction (SCR) and Nonselective Catalytic Reduction (NSCR). The SCR uses urea that is injected in the exhaust flow and reacts with the NOx gases in the catalytic converter. NSCR employs urea or ammonia at 1000ºC that reduces NOx, CO and HC to nitrogen, water, and CO_2.

1.5.5.3. Particulate emissions mitigation

Particulate emissions are verified by smoke opacity which is mitigated with diesel particulate filters (DPFs) or diesel oxidation catalyst (DOC).

1.6. NRMM Market overview

Has stated before, NRMM has been subjected to less restrictive emissions regulations compared to on-road vehicles. However, OEMs in the NRMM market are anticipating increasing decarbonization pressure because of their customers. Major mining companies have set ambitious decarbonization targets. In other sectors such as construction and agriculture there are also some zero-emissions solutions [15].

Engines today are as much as 98% less polluting than those manufactured in 2000 when one considers PM and NOx.

Following there is an overview of the achievements in the NRMM industry to this date.

1.6.1. Dual Fuel Injectors

Some manufacturers have developed dual fuel injectors. Woordward Inc (woodward.com) has developed a high-pressure dual fuel injector capable of working with diesel, methane, LPG, methanol and ammonia by varying the injected quantity according to the calorific value of the fuel. The injector nozzle has three concentric gas needles and one central diesel needle [67]. The gas injector system withstands up to 600 bar and diesel system up to 2000bar.

Westport along with BorgWagner developed the HPDI[tm] system for CNG and H2 dual injection with diesel. The CNG system is already used in Volvo road trucks. Westport states that the target is to use the same injector hardware in both CNG and H_2. They state that ICE will have more power, torque, efficiency, no difference in thermal and mechanical load compared to diesel operation.

1.6.2. Caterpillar (CAT)

Caterpillar Inc. is the world's leading manufacturer of construction and mining equipment, off-highway diesel and natural gas engines, industrial gas turbines and diesel-electric locomotives.

Most CAT engines accept Diesel with B20 blends, including Tier 4 engines. For B100 biodiesel, or neat biodiesel (100% FAME) it's acceptable in many Cat engines as for the specification ASTM D7651[29].

Also, CAT is working with Chevron to develop hydrogen demonstration projects in transportation and stationary power applications, including prime power [73].

Caterpillar Bulldozer D11XE prototype, is a large dozer and it's equipped with an electric drive powertrain that can achieve a reduction in fuel consumption by up to 25% with a machine lifespan up to 20% longer.

In underground mining, where it's difficult to have adequate ventilation, they have introduced a diesel-electric underground loader, along with the forward-looking R1700 XE — a high productivity, zero exhaust emissions loader with the industry's only onboard battery and a portable equipment charger. It will complement a first-of-its-kind battery electric, zero exhaust emissions underground truck to provide a fully electric underground load and haul solution.

In open pit mining, Caterpillar has successfully demonstrated an electric 793 large mining truck. Fully loaded to its rated capacity, the truck achieved a top speed of 60 km/h (37.3 mph). The loaded truck travelled 1km (0.62 mile) up a 10% grade at

12km/h (7.5 mph). The truck also performed a 1km (0.62 mile) run on a 10% downhill grade [74].

Sandvik Mobile Crushers and Screeners, use the Cat® C-Series engines supplied to power its mining and construction equipment and can run on renewable and alternative fuels including hydrotreated vegetable oil (HVO) certified to EN15940 or ASTM D975. Sandvik have successfully completed testing on their range of machines to confirm that they can operate with HVO without modifications to either the engines or the fuel tanks. This helps Sandvik and their customers to reduce the net carbon dioxide (CO_2) emissions by up to 90% compared with conventional diesel (Caterpillar Press Release 550PR22) [75].

1.6.3. Cummins

Cummins announced the testing of hydrogen internal combustion (ICE) technology in July 2021 with the B6.7H hydrogen engine for medium-duty trucks. In the IAA Hannover fair 2022, Cummins exhibit the larger X15H hydrogen engine aimed at heavy-duty trucks up to 44T GVW, with a top rating of 530 hp (395 kW) and an impressive peak torque of 2600 Nm [76].

1.6.4. CASE Construction Equipment (CASE CE)

In CONEXPO-CON/AGG 2020, CASE CE introduced the electric Backhoe CASE 580EV with the same breakout forces of the diesel version. It runs on a 480V 90kW.h lithium battery and has 8h autonomy. In 2022 it’s still not available on the market.

Also presented an electric mini excavator.

1.6.5. FPT (CNH/Iveco Group)

FPT Industrial is dedicated to the design, production and sale of powertrains for on-road and off-road vehicles, as well as marine and power generation applications. FPT Industrial offers the most complete lineup of natural gas engines on the market for industrial applications, with power that goes from 50 to 460 hp. [77] FPT was the first to introduce gas ICE with around 50% market share, on highway and off highway.

In the IAA fair, September 2022, FTP presented a multifuel single base engine, diesel natural gas and hydrogen for several markets. The Brand's new XC13 is FPT Industrial's first multi-fuel single base engine. From diesel to natural gas – including biomethane – hydrogen, and renewable fuels, the base engine has been designed with multiple versions to offer maximum component standardization and easy integration into the final product. The new XC13 engine positions itself as a primary contributor to achieving short and mid-term fleet CO_2 emissions targets. The diesel version delivers best-in-class performance up to 600 hp and 2850 Nm. The methane version delivers up to 520 hp and 2500 Nm. CO2 emissions reductions stands at 9% for the diesel unit and 10% for the methane model, but the latter can achieve net-zero CO_2 emissions when fueled by biomethane. The natural gas version offers diesel-such as performance. The XC13 will be ready for Euro VII with simple upgrades. [78]

FPT powers a methane tractor for CNH under the energy independent farm concept. Farms that produce their own gas. The engine is a NEF 6.7-liter engine specifically developed for agricultural applications. It also offers operators fuel flexibility and can run on either biomethane or compressed natural gas (CNG).

1.6.6. Deere

As this date, all John Deere engines can use biodiesel in different blending's according to the stage of development. Stage V engines operated within the European Union can use biodiesel blends up to 8% (B8). Final Tier 4/Stage IV and Interim Tier 4/Stage III B engines can use biodiesel concentrations up to 20% (B20). Tier 3/Stage III A and lower tier engines can use up to 100% (B100) biodiesel [79].

Deere has made an equity investment in the company ClearFlame Engine Technologies to the develop of clean engine technology. ClearFlame's solution enables low-carbon fuels such as ethanol to be easily integrated into compression ignition [80].

Also has developed with Amogy®, a mid-sized agricultural tractor with a 100kW ammonia to power system. The system is comprised of a standard liquid-storage tank and highly efficient ammonia-cracking modules integrated into a hybrid fuel cell system, which can provide consistent primary power for several hours per refueling [81].

1.6.7. DEUTZ & KEYOU

DEUTZ is one of the world’s leading manufacturers of drive systems for off-highway applications. Originally founded as N.A. Otto & Cie. in Cologne, Germany, in 1864, DEUTZ AG is now the world's oldest engine company. Its core competencies are the development, production, and distribution of drive solutions in the power range up to 620 kW for off-highway applications.

DEUTZ engines that meet EU stage V are approved for HVO biofuel [82].

DEUTZ and KEYOU developed an Hydrogen ICE (TCG7.8H2) from its diesel-powered version TCD 7.8, in-line six-cylinder. The diesel injectors were replaced by centrally positioned spark plugs. The new gasoline engine pistons achieve a compression ratio of 1:10 and the rugged diesel power pack allows pressure loadings of up to a peak combustion pressure of 180 bar. The engine is supercharged by a single-stage turbocharger including electronic wastegate with a boost pressure of up to 3,75 bar absolutes. The engine is additionally equipped with charge air cooling and an externally cooled high pressure EGR. The variable mixture of air, hydrogen and exhaust gas is generated by cylinder selective (MPI) injection via the hydrogen intake manifold. Charge control, and thus control over the power output, is exercised in the classical manner by the throttle valve and by electronic boost pressure control. There is also an SCR catalytic converter to reduce nitrogen oxide levels [30].

The engine achieves maximum power output of 234 kW at 2250 rpm and maximum torque of 1325 Nm at 1300 rpm. Optimum thermodynamic efficiency of 40% is achieved at 1250 rpm/min and 1200 Nm, corresponding to specific hydrogen consumption of 74.7 g/kWh. This applies especially when running the engine on hydrogen when the fuel-air-exhaust gas mixture, the ignition angle, throttle valve, EGR adjuster and wastegate adjuster all need to be simultaneously adjusted to the most efficient setting for dynamic operation. DEUTZ announced for 2024 the full production of hydrogen engines for stationary applications such as generators, with plans to extend their use to mobile applications in the future. They’ve chosen automotive supplier MAHLE to supply hydrogen engine components [83].

1.6.8. Doosan (Hyundai Doosan Infracore) (HDI)

HDI stage 5 engines use post treatment DPF+SCR systems. Some engines run on renewable LPG/CNG/LNG. They plan to have a hydrogen engine and tank systems with 300 kW of power generation and 11 liters of displacement by 2024 and start mass production in 2025.

1.6.9. Hyundai Construction Equipment (HCE)

HCE presented in BAUMA 2022 a hydrogen fuel cell wheel excavator HW155H (14t) to be commercially available in 2025-2026. HCE employs Cummins ICEs in their machines.

1.6.10. JCB

JCB announced in July 2020 that it has developed the construction industry's first ever hydrogen powered excavator. The prototype, a 20-tonne 220X excavator, was powered by a hydrogen fuel cell.

They also developed a backhoe and telehandler with a hydrogen ICE, a first also in construction industry, presented in June 2022. Using and adapting established engine technology with readily available components, hydrogen is combusted and power is delivered in exactly the same way as a diesel engine [84].

1.6.11. Liebherr

Liebherr, for conventional diesel engines, from stage IV and V on, has chosen the path of not using EGR and maximize the performance of SCR with better fuel economy that overcompensates for higher consumption of AdBlue [85].

In BAUMA fair 2022 Liebherr introduced the hydrogen ICE that have been in testing since 2020. The use of well-known platforms leads to reduced development complexity and costs. The new engines received the denomination H964 and H966 and were developed with Mahle-Powertrain Jet Ignition® system[42]. The H966 (13,5L) was developed on a R9xx with PFI. Then they developed the hydrogen DI ICE H964 (9L, Compression Ratio 11 to 13) [86] [7].

Both developments rely on a dedicated double stage charging to ensure an ultra-lean combustion, which leads to lower NOx emissions. The single stage configuration with EGR is an alternative solution under investigation. This less complex and more compact solution could also be a relevant step towards ultra-low NOx emission. [7]

1.6.12. Rolls-Royce (MTU)

For NRMM the MTU series 4000 are ready to run on hydrogen and synthetic paraffinic diesel fuels, including HVO.

1.6.13. Volvo Construction Equipment

Volvo Construction Equipment (Volvo CE) has started testing of the world's first fuel cell articulated hauler prototype, the Volvo HX04 and is the result of a research project running between 2018 and 2022. Infrastructure for hydrogen is still in development (Press release Jun 2022) [87].

Volvo CE also launched the A30G articulated hauler built using fossil-free steel, using the existing manufacturing process, with fossil-free steel from Swedish steel company SSAB.

Also, it has on their portfolio the ECR18 Electric and EC18 Electric compact excavators and the L25 Electric and L20 Electric compact wheel loaders available in select Europe and North America markets, and the ECR25 Electric, available in select Europe, North America and Asia markets, together with the EC55 Electric excavator, available for now only in China. For larger equipment they only have the EC230 excavator in China and Norway [88].

1.6.14. Volvo Penta

Volvo Penta is a global manufacturer of engines and complete power systems for boats, vessels, and industrial applications. They have worked together with CMB.tech in pilot projects since 2017 successfully adapting Volvo Penta engines to run as a dual-fuel hydrogen and diesel solution via the conversion kit provided by CMB.TEC. If hydrogen is not available, the engine continues to run on traditional fuel, safeguarding productivity[89].

At BAUMA 2022 fair in Munich, Germany, Volvo Penta showcased a dual-fuel engine utilizing hydrogen as a renewable fuel source. Based on the existing D8 - an inline six-cylinder, 7.7 L diesel engine - the dual-fuel configuration reduces CO_2 emissions as much as 80%, the company stated. If hydrogen is unavailable, the engine can continue to run on traditional diesel. [90]

1.6.15. XCMG

XCMG, 4th world largest construction machinery manufacturer has been testing 72t electric mine truck, as announced in August 2022 and also small electric excavators in cooperation with Cummins Inc..

The following chapter of this study primarily focuses on the investigation of dual-fuel combustion, specifically the combination of diesel and hydrogen (Diesel + H_2), in a conventional CI engine. The research aims to comprehensively analyze how this fuel mixture influences the performance of an engine traditionally powered by fossil diesel. This work is motivated by the pressing need to transition towards more sustainable and eco-friendlier NRMMs, given the environmental concerns associated with diesel engines. The use of hydrogen, as one of the alternative fuels of significant interest, holds the potential to address these concerns, because as a fuel, its clean-burning nature, high energy content, and minimal greenhouse gas emissions, makes it a promising candidate for reducing the environmental impact of ICEs.

The engine chosen for this research is a 2.5L turbocharged CI engine, mechanical fuel injection, which is a common power source in light duty industrial machinery.

CHAPTER II – EXPERIMENTAL DUAL FUEL CI ENGINE

2.1. Introduction

Has stated before in this work, internal combustion engines (ICEs) have long been a cornerstone of transportation and power generation, with diesel engines playing a pivotal role due to their robustness and efficiency. However, the global pursuit of sustainable energy solutions and the imperative to reduce greenhouse gas emissions have driven extensive research into alternative fuels and engine technologies. Among these alternatives, hydrogen has emerged as a promising candidate.

This study is aimed at comprehensively investigating the impact of dual fuel combustion, specifically the combination of fossil diesel and hydrogen (Diesel + H_2), on the performance of a conventional Compression Ignition (CI) engine that traditionally runs on fossil diesel fuel. The objective is to provide a systematic and data-driven analysis of the engine's behavior when subjected to this novel fuel mixture. The collected data will facilitate a thorough evaluation of how the addition of hydrogen influences critical engine parameters, including efficiency and emissions.

The reason behind this research is rooted in the pressing need to transition towards more sustainable and eco-friendlier Non-Road Mobile Machinery (NRMM). Diesel engines, although with already strict directives, have been associated with emissions of pollutants and greenhouse gases that contribute to environmental degradation and public health concerns. The integration of hydrogen into the combustion process offers the potential to mitigate these environmental impacts while maintaining or even enhancing engine performance.

One of the researched parameters was fuel efficiency. This key parameter is one of the quality indicator in vehicles[91] and is essential for the reduction of fossil fuel GHG emissions and how can dual-fuel systems can contribute to it. Typically fuel economy is measured in terms of fuel consumption per unit of work done, in this study it was measured in milliliters per second and converted to liters/hour (l/h) for better interpretation since it’s the metrics most used in industrial ICEs[91]. The hydrogen flow input was set in levels ranging from 0 to 15, these levels relate to a constant hydrogen flow ranging from 1 to 15 l/min.

Another parameter was the volumetric efficiency (ηV) since it's a crucial parameter in the design and analysis of internal combustion engines. It measures the effectiveness of an engine's ability to aspirate a volume of air(V_a) into the cylinders compared with the quantity of theoretical air (V_t) the engine would draw [65]. This efficiency is vital because the amount of air that can be drawn into the cylinders directly impacts an engine's power output and overall performance. Volumetric efficiency is given by:

$$\eta V = {}^{V_a}/_{V_t}$$

where: V_a – Obtained from the flow sensor.

V_t – Theoretical air the engine can draw, given by:

$$V_t = \frac{Engine\ Capacity\ (Liters) \times\ rpm}{2}$$

Other evaluated parameters where the gaseous emissions of HC, CO_2, H_2, O_2, NOx and opacity. They were measured with two equipment's brand TEXA, one being model GASBOX (compliant with M.I.D. 2014/32/EC), and model OPABOX (compliant with ISO11614, 72/306CEE, SAE J 1667) for opacity.

This chapter is organized as follows:

- **Introduction:** Provides an overview of the background, research objectives, and the significance of exploring alternative fuels like hydrogen in CI engines.
- **Research Objectives:** Clearly defines the research objectives, focusing on engine operating characteristics and emissions analysis.
- **Experimental Setup:** Describes the systematic data collection methodology, including details on the engine, equipment used, and data recording.
- **Discussion and Results:** Analyzes the findings of the study, covering topics such as fuel efficiency, volumetric efficiency, and emissions, supported by data tables and charts.

- **Conclusions:** Summarizes the key outcomes of the research, highlighting the implications of hydrogen addition for engine performance and emissions.
- **Future Work:** Suggests areas for future research to build upon the insights gained in this study.
- **Bibliography:** Lists the sources and references used in this research for further reading.

2.2. Research Objectives

The research objective is the analysis of the engine's operating characteristics at no load in a Dual Mode Operation. This included the evaluation of parameters such as fuel (diesel and hydrogen) consumption (energy input), air consumption and emissions. The emissions analysis is a key aspect for internal combustion engines since they have significant environmental consequences. The research aims to investigate how the introduction of hydrogen influences exhaust emissions, including reductions in harmful pollutants such as nitrogen oxides (NOx).

Since engine was tested at no load conditions, not all parameters were evaluated such as engine efficiency, power output and torque, combustion stability, hydrogen ignition delay (research done with hydrogen port fuel injection), and heat release rates, but the focus was on operating characteristics and emissions analysis.

2.3. Experimental setup CI engine with dual fuel - Diesel+H2

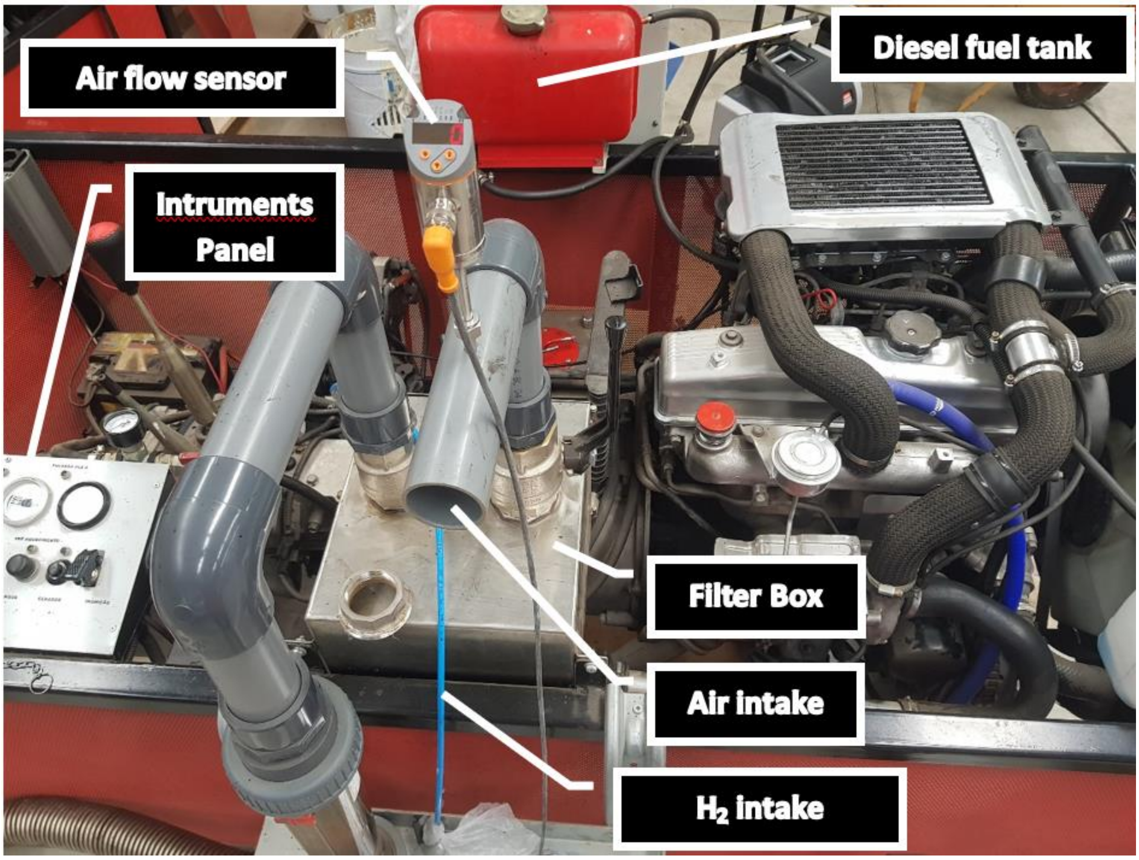
The research methodology involved the systematic collection of data, using a 2.5L turbocharged CI engine with mechanical injection. Key parameters, including air flow, hydrogen flow and pressure, rpm, and diesel fuel consumption, were continuously monitored and recorded. The data collected served as the basis for analysis and conclusions regarding the effects of hydrogen addition on engine performance and emissions. The data was collected with the previous mentioned equipment and computed in excel for analysis.

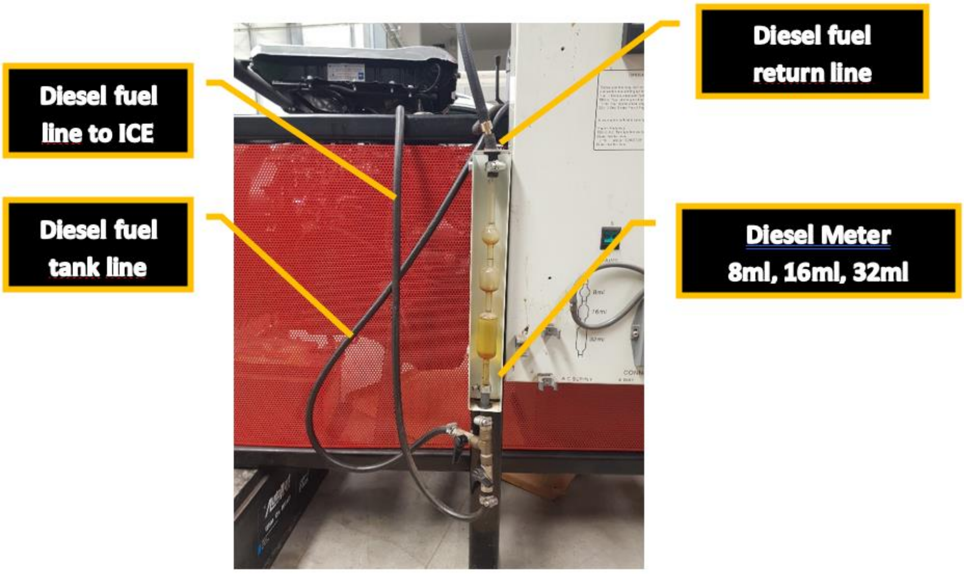
Table 10 – Main results from tests

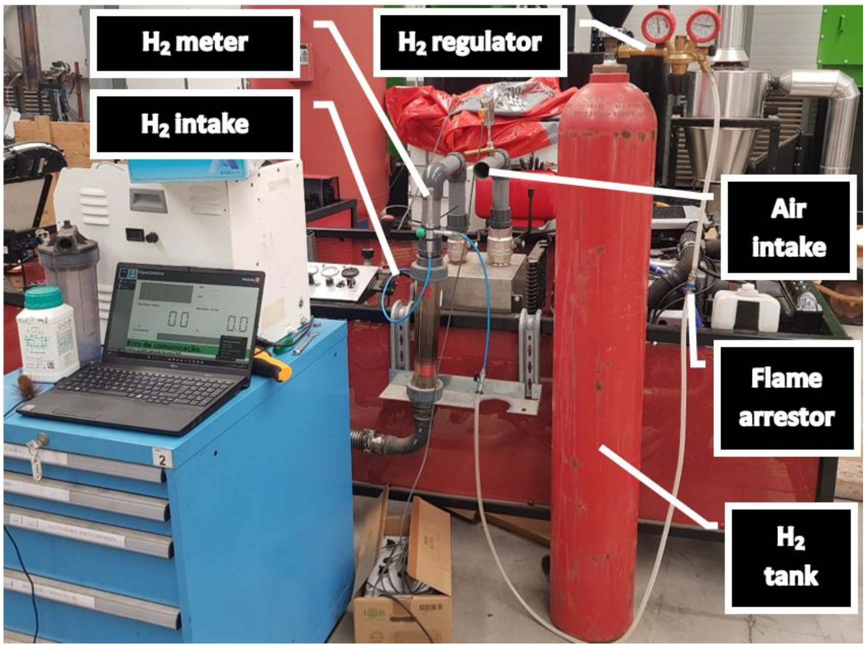
Parameter	Change	
Fuel efficiency		-28.2%
Volumetric efficiency		-15.4 to +23.4%
Energy Input		-17 to +22.0%
Exhaust emissions	CO	-33 to -50%
	CO_2	-2 to -7%
	HC	-6 to -7%
	NOx	-64 to -83%

The test bench consists of the diesel engine installed in a wheeled frame with all necessary running components, such as battery, fuel filter and pump, mechanical fuel injection pump, air filter box, intercooler, etc. The following pictures shows the test bench with the added diesel fuel tank with feed lines, graduated meters and return lines, also H2 line with pressure regulator and flow regulator.

Figure 5 - Test bench setup

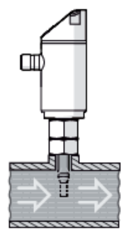






The input air was obtained with an air flow sensor brand IFM model SA4120 with a repeatability of ± (3 % MW + 0,6 % MEW). It was installed on the air intake of the engine before the air filter at 200mm distance from the closest interference, with 15mm immersion and was programed for the 40mm intake diameter pipe. This sensor monitored air flow (m^3/h) and temperature (ºC).

Figure 6 - IFM SA4120



The rpm was read from engine test bench and diesel fossil fuel (EN590) consumption was registered from graduated beakers. The H_2 (99.999%) was supplied into the air filter box by a 250bar hydrogen tank thru a pressure and flow regulator. The data was manually collected during the experiments and included on an Excel spreadsheet.

The experiment was conducted with rpm values of 1000, 1250, 1500, 1750 and 2000 in only Diesel mode. After a steady state was obtained, the values for air flow, air temperature, rpm and Diesel fuel consumption for different values of hydrogen flow was registered. Careful analysis was performed because the data was not always linear or had a direct correlation leading to further tests to better validate and understand the reason of some results.

Table 11 – Diesel and gases parameters

		Diesel (EN590)	**Gases**		
Chemical Structure (approx.)		$C_{12}H_{23}$	H_2	O_2	N_2
Density	**g/mol**		2.016	32	28
	g/l	833	0.082	1.308	1.144
Lower heating value	**MJ/kg**	43	120.1		
Density @ 15ºC	**kg/m³**	838.8	17.5		

The rpm increase for different H_2 levels was calculated by the following formula:

$$RPM_{increase}(\%) = 1 - \frac{RPM_{H0}}{RPM_{Flow}}$$

where:

RPM_{H0} – No hydrogen injection

$RPM_{H_{flow}}$ – Hydrogen flow injection

In cylinder pressure was not evaluated. The advantage of doing so is the analysis of engines efficiency by the Indicated Mean Effective Pressure (IMEP). IMEP is an indicator of the average pressure exerted on the piston during the power stroke of the engine cycle. It provides valuable insights into the engine's thermodynamic efficiency and overall performance. For example, a higher IMEP indicates greater efficiency, meaning that more energy from the fuel is being converted into useful work. The test bench could be further improved with an in-chamber piezo sensors such as Kistler Type 6125C… and a proper data acquisition software and hardware. This sensor is a ground-isolated high-temperature pressure sensor with integral connecting cable (available option with oil-proof) for measuring cylinder pressures in combustion engines. It doesn´t need additional cooling, has low thermal shock error, very low load-change drift, sensitivity of 37 pC/bar and a pressure range up to 300 bar. This uncooled sensor is suitable for accurate measurement in gasoline and diesel engines. Its ground-isolated design makes it ideal for test stands with ground loop problems. The shoulder sealing of this sensor allows it to be mounted with its front flush in the cylinder head. This pressure sensor can be can be mounted flush with the wall of the combustion chamber or recessed in an M10x1. [92]

Figure 7 - Kistler 6125C, in chamber pressure sensor

2.4. Results and discussion

2.4.1. Fuel efficiency

The relation between the hydrogen percentage and fuel efficiency (economy) in a dual-fuel diesel-hydrogen engine can vary depending on several factors. This key parameter, fuel efficiency, is one of the quality indicator in vehicles[91] and essential for the reduction of fossil fuel GHG emissions and dual-fuel systems can contribute to it. Typically fuel economy is measured in terms of fuel consumption per unit of work done, in this study it was measured in milliliters per second and converted to liters/hour (l/h) for better interpretation since it's the metrics most used in industrial ICEs[91]. The hydrogen flow input was set in levels ranging from 0 to 15, these levels relate to a constant hydrogen flow ranging from 1 to 15 l/min. The average temperature during testing was 35ºC (308,15K) and considering R = 0,0206 L.atm/mol.K and pressure 1 atm, from ideal gas law, $P \times V = n \times R \times T$:

Table 12 – Hydrogen flow in volume (l/min), mass(g/min) and Energy (MJ/min)

H_2		
Flow		Energy
l/min	g/min	MJ/min
1	0.082	0.010
3	0.247	0.030
5	0.412	0.049
7	0.577	0.069
9	0.742	0.089
11	0.906	0.109
13	1.071	0.129
15	1.236	0.148

The following tables resume the data from all rpm tests.

Table 13 – Data at 1000 rpm

Hydrogen			Diesel			Energy Input	
Flow		Energy	Flow	Energy			
l/min	g/min	MJ/min	g/min	MJ/min	var%	% Diesel	%H2
0	0	0	12.529	0.539	0	100.0%	0.0%
1	0.082	0.010	12.419	0.534	-0.9%	98.2%	1.8%
3	0.247	0.030	12.344	0.531	-1.5%	94.7%	5.3%
5	0.412	0.049	12.202	0.525	-2.6%	91.4%	8.6%
7	0.577	0.069	12.051	0.518	-3.8%	88.2%	11.8%
9	0.742	0.089	11.952	0.514	-4.6%	85.2%	14.8%
11	0.906	0.109	11.920	0.513	-4.9%	82.5%	17.5%
13	1.071	0.129	11.999	0.516	-4.2%	80.0%	20.0%
15	1.236	0.148	11.856	0.510	-5.4%	77.5%	22.5%

Table 14 – Data at 1250rpm

Hydrogen			Diesel			Energy Input	
Flow		Energy	Flow	Energy			
l/min	g/min	MJ/min	g/min	MJ/min	var%	% Diesel	%H_2
0	0	0	14.776	0.635	0	100.0%	0.0%
1	0.082	0.010	14.473	0.622	-2.1%	98.4%	1.6%
3	0.247	0.030	14.415	0.620	-2.4%	95.4%	4.6%
5	0.412	0.049	14.130	0.608	-4.4%	92.5%	7.5%
7	0.577	0.069	13.670	0.588	-7.5%	89.5%	10.5%
9	0.742	0.089	13.473	0.579	-8.8%	86.7%	13.3%
11	0.906	0.109	13.751	0.591	-6.9%	84.5%	15.5%
13	1.071	0.129	13.233	0.569	-10.4%	81.6%	18.4%
15	1.236	0.148	12.624	0.543	-14.6%	78.5%	21.5%

Table 15 – Data at 1500rpm

Hydrogen			Diesel			Energy Input	
Flow		Energy	Flow	Energy			
l/min	g/min	MJ/min	g/min	PCI MJ/min	var%	% Diesel	%H_2
0	0	0	21.125	0.908	0	100.0%	0.0%
1	0.082	0.010	20.424	0.878	-3.3%	98.9%	1.1%
3	0.247	0.030	18.243	0.784	-13.6%	96.4%	3.6%
5	0.412	0.049	17.396	0.748	-17.7%	93.8%	6.2%
7	0.577	0.069	17.009	0.731	-19.5%	91.3%	8.7%
9	0.742	0.089	17.138	0.737	-18.9%	89.2%	10.8%
11	0.906	0.109	17.039	0.733	-19.3%	87.1%	12.9%
13	1.071	0.129	16.655	0.716	-21.2%	84.8%	15.2%
15	1.236	0.148	16.147	0.694	-23.6%	82.4%	17.6%

Table 16 – Data at 1750rpm

Hydrogen			Diesel			Energy Input	
Flow		Energy	Flow	Energy			
l/min	g/min	MJ/min	g/min	MJ/min	var%	% Diesel	%H_2
0	0	0	28.261	1.215		100.0%	0.0%
1	0.082	0.010	26.060	1.121	-7.8%	99.1%	0.9%
3	0.247	0.030	24.633	1.059	-12.8%	97.3%	2.7%
5	0.412	0.049	24.357	1.047	-13.8%	95.5%	4.5%
7	0.577	0.069	24.259	1.043	-14.2%	93.8%	6.2%
9	0.742	0.089	23.394	1.006	-17.2%	91.9%	8.1%
11	0.906	0.109	22.407	0.964	-20.7%	89.8%	10.2%
13	1.071	0.129	22.046	0.948	-22.0%	88.1%	11.9%
15	1.236	0.148	20.553	0.884	-27.3%	85.6%	14.4%

Table 17 – Data at 2000rpm

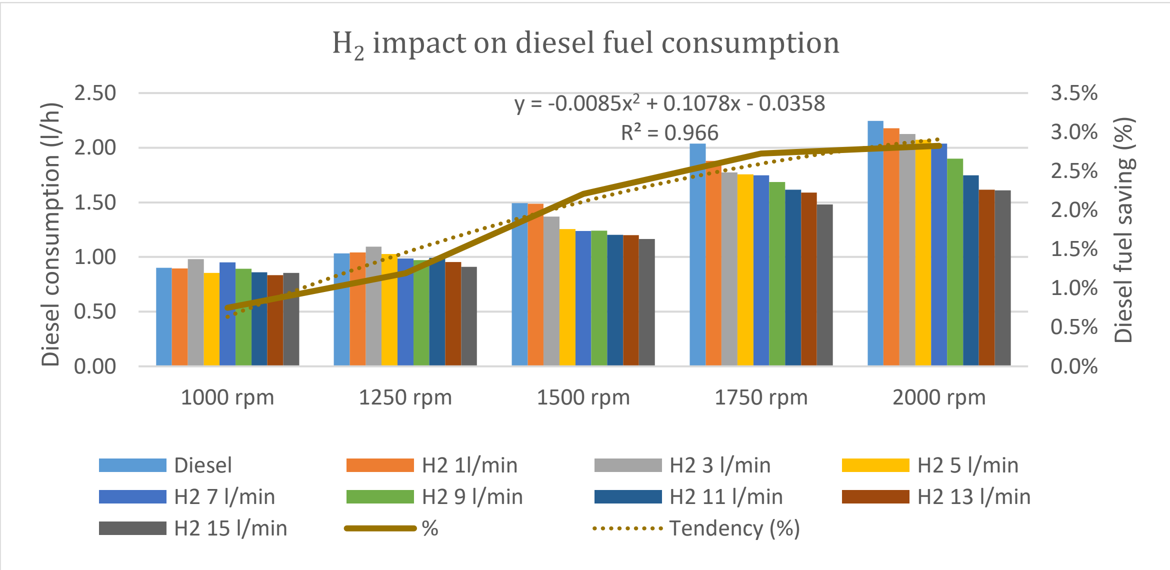
Hydrogen			Diesel			Energy Input	
Flow		Energy	Flow	Energy			
l/min	g/min	MJ/min	g/min	MJ/min	var%	% Diesel	%H_2
0	0	0	31.148	1.339		100.0%	0.0%
1	0.082	0.010	30.207	1.299	-3.0%	99.2%	0.8%
3	0.247	0.030	29.476	1.267	-5.4%	97.7%	2.3%
5	0.412	0.049	28.753	1.236	-7.7%	96.2%	3.8%
7	0.577	0.069	28.261	1.215	-9.3%	94.6%	5.4%
9	0.742	0.089	26.354	1.133	-15.4%	92.7%	7.3%
11	0.906	0.109	24.264	1.043	-22.1%	90.6%	9.4%
13	1.071	0.129	22.411	0.964	-28.0%	88.2%	11.8%
15	1.236	0.148	22.350	0.961	-28.2%	86.6%	13.4%

Table 18 helps illustrate how fuel economy changes with varying levels of hydrogen. The table lists hydrogen flow at different engine speeds, i.e., 1000, 1250, 1500, 1750 and 2000 rpm. The fuel economy values are given in % of diesel saved. ***Table 18*** illustrates the diesel fuel savings across all rpms at different H_2 flows.

Table 18 – Diesel fuel saving (l/h) vs rpm and H_2

		1000 rpm	1250 rpm	1500 rpm	1750 rpm	2000 rpm
Hydrogen flow (l/min)	1	-0.9%	-2.1%	-5.4%	-7.8%	-3.0%
	3	-1.5%	-2.4%	-11.6%	-12.8%	-5.4%
	5	-2.6%	-4.4%	-17.6%	-13.8%	-7.7%
	7	-3.8%	-7.5%	-18.6%	-14.2%	-9.3%
	9	-4.6%	-8.8%	-18.6%	-17.2%	-15.4%
	11	-4.9%	-6.9%	-21.0%	-20.7%	-22.1%
	13	-4.2%	-10.4%	-21.2%	-22.0%	-28.0%
	15	-5.4%	-14.6%	-23.6%	-27.3%	-28.2%

Figure 8 – Fuel consumption vs H_2 flow vs rpm



As observed in Figure 8, fuel economy varies significantly with both hydrogen flow level and engine speed. The percentage change in fuel economy between no hydrogen and 15 l/min varies from 0.9% to 28.2% depending on engine speed. In some cases, adding hydrogen (higher hydrogen flow) appears to better improve fuel economy, e.g., higher than 1250 rpm. However, this improvement isn't uniform across all engine speeds and hydrogen levels. For example, at 1000 rpm, fuel economy is lower with hydrogen, and it was observed that the ICE had misfires and black smoke indicating an incomplete combustion. This was most likely due to incorrect dual fuel parameters necessary to achieve proper ignition and combustion. The air-fuel mixture may not be well-mixed or not having the right balance between diesel, hydrogen and air in the air-fuel mixture, i.e., too lean or too rich (not enough oxygen), thus having low thermal efficiency [93]. Low thermal efficiency means that a significant portion of the energy from the fuel was wasted as heat, which reduces the engine's ability to perform mechanical work.

Also, at higher rpm the fuel economy decreases because the H_2 flow was not proportional to the rpm, meaning that with proper engine management controlling the H_2 flow would yield even better fuel economy.

Further analysis and consideration should be carried out with other factor such as engine calibration, combustion efficiency, emissions, and other engine parameters that were not available due to absence of the necessary instrumentation.

Another aspect could be related to the fact that diesel ICEs typically have a high compression ratio, which is essential for diesel combustion. Because of fixed compression ratio, the air/fuel mixture may need adjustment to accommodate the different combustion characteristics of hydrogen and should be further researched with the help of in chamber pressure sensors (**Erro! A origem da referência não foi encontrada.**).

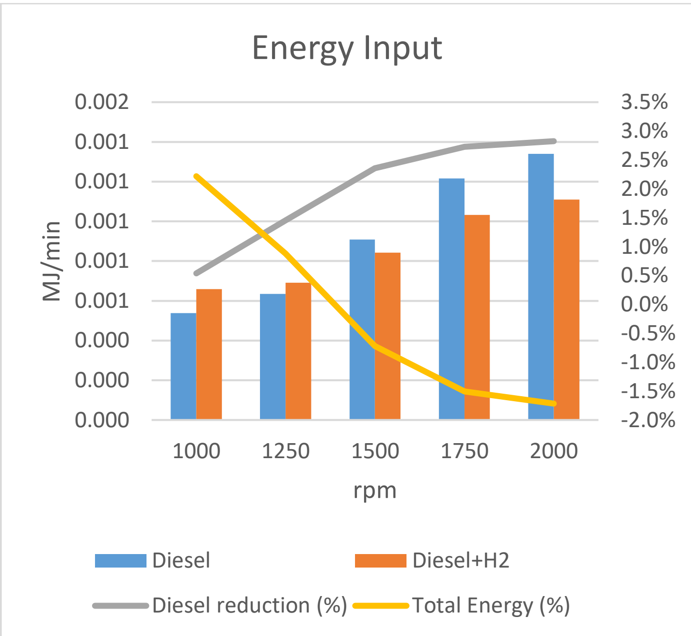
Fuel efficiency is influenced by various factors, including the engine's operating conditions and the properties of the fuels used. For example, examining the relationship between hydrogen percentage and fuel economy, hydrogen has a higher energy content per unit mass compared to diesel fuel (Table 11). Therefore, increasing the percentage of hydrogen in the fuel mixture can potentially improve fuel economy because hydrogen contributes with more energy for the same mass of fuel.

The hydrogen energy fraction was calculated using lower heating values of diesel and hydrogen fuels (Table 11). Table 19 and **Erro! A origem da referência não foi encontrada.** resumes the H_2 energy input in percentage of energy supplied by the hydrogen to the combustion and, with the increase of hydrogen flow the higher the substitution of diesel fuel energy.

Table 19 – Hydrogen Energy Input

		1000rpm	1250rpm	1500rpm	1750rpm	2000rpm
Hydrogen flow (l/min)	1	2%	2%	1%	1%	1%
	3	5%	4%	4%	3%	2%
	5	8%	7%	6%	4%	4%
	7	11%	10%	8%	6%	5%
	9	14%	13%	10%	8%	7%
	11	17%	15%	13%	10%	9%
	13	19%	18%	15%	12%	11%
	15	22%	21%	17%	14%	13%
Total Energy used (Diesel + H_2)		+ 22%	+ 9%	- 7%	-15%	-17%

Figure 9 – Dual fuel Input Energy vs rpm, diesel fuel saving

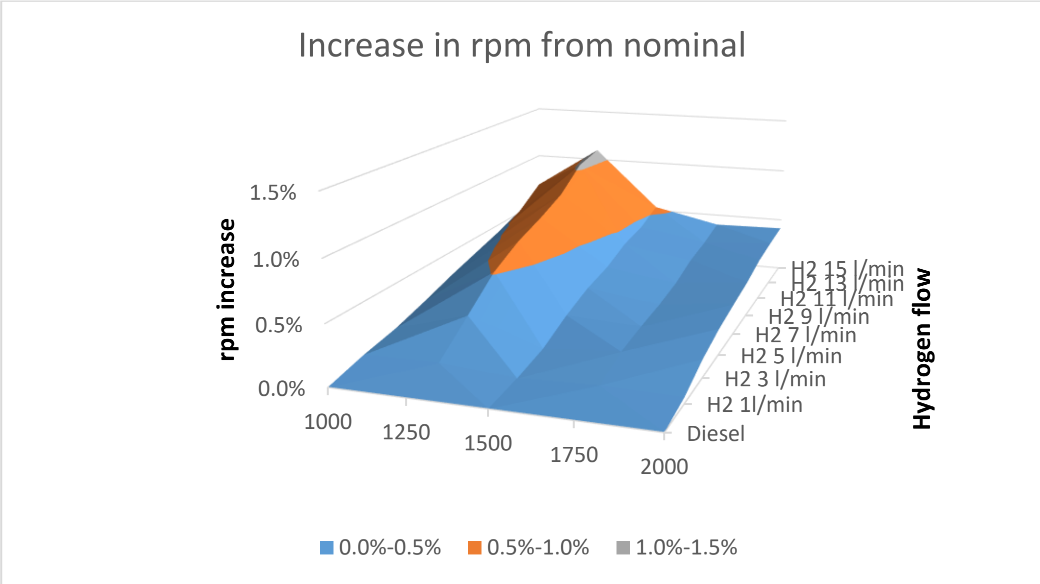


As shown in Figure 9**Erro! A origem da referência não foi encontrada.** the percentage of hydrogen energy decreases as engine speed (rpm) increases, this is because the hydrogen flow rate was constant for predetermined levels for all rpm tests, but as engine speed (rpm) increases, the engine's air intake volume per unit of time also increases and by maintaining a constant flow rate of hydrogen (volume of hydrogen injected) while the air intake volume increases, the relative proportion of hydrogen to the total energy decreases. Furthermore, as observed form the data in Table 18 the diesel fuel consumption also increased at higher rpm to match the higher air intake. This is also consistent with the data from Table 20 where it's observed that the percentage of rpm increase dropped from 1500 to 2000 rpm, from 11% at 1250rpm to 4.1% at 2000rpm.

Table 20 – % increase in rpm with H_2 flow

		1000rpm	1250rpm	1500rpm	1750rpm	2000rpm
Hydrogen flow (l/min)	1	0.7%	0.8%	0.3%	0.6%	0.5%
	3	1.2%	3.0%	0.9%	1.4%	1.5%
	5	2.0%	5.2%	2.0%	1.7%	2.2%
	7	2.8%	6.5%	2.8%	1.9%	2.6%
	9	3.6%	7.4%	3.2%	2.3%	3.0%
	11	4.3%	8.5%	4.1%	3.0%	3.6%
	13	5.2%	10.4%	4.5%	3.4%	3.9%
	15	6.9%	11.0%	5.4%	4.0%	4.1%

Figure 10 - Percentage of rpm increase from nominal.



Initially, at low hydrogen levels, adding small amounts of hydrogen (1 to 3 l/min) to the air-fuel mixture may have a relatively smaller impact on engine speed. The engine's behavior is likely more similar to its baseline operation (Diesel only) with minimal changes in rpm. At higher hydrogen levels, as the percentage of hydrogen in the mixture increases (5 l/min and beyond), the engine begins to respond more significantly to the hydrogen addition, resulting in larger increases in engine speed. This is because hydrogen has different combustion characteristics compared to diesel fuel and can influence the combustion process more prominently as its concentration in the mixture rises. However, at higher hydrogen flows (11 to 15 l/min), the rate of increase in engine speed per unit of added hydrogen starts to decrease. This is because, as stated before, the hydrogen flow level was constant regardless of engines rpm. So, at higher rpm, hydrogen energy contribution decreases and for example, comparing hydrogen highest flow with 100% diesel at 2000rpm, there is a 10% drop in H_2 energy contribution (Table 19).

The observed trend highlights the importance of finding the optimal balance in the air-fuel mixture when using hydrogen in a dual-fuel diesel engine. Too little hydrogen may not result in significant performance improvements, while hydrogen injection rate should be correlated with engine speed.

Engine setup parameters are crucial to achieving the desired performance and efficiency targets while considering factors like engine speed, hydrogen concentration, and the engine's combustion dynamics. Typically, when adjusting the percentage of hydrogen energy in a dual-fuel engine, it should be possible to increase the hydrogen energy contribution at higher rpm. This observation is consistent with how engine behavior can change with varying engine speeds, and it highlights the importance of proper calibration and adjustment of the dual-fuel system to maintain a desired hydrogen-to-diesel ratio across different operating conditions. It's also essential to consider the engine's dynamic behavior, combustion characteristics, and the varying demands on the air-fuel mixture at different rpm levels for optimizing performance and emissions in dual-fuel configurations.

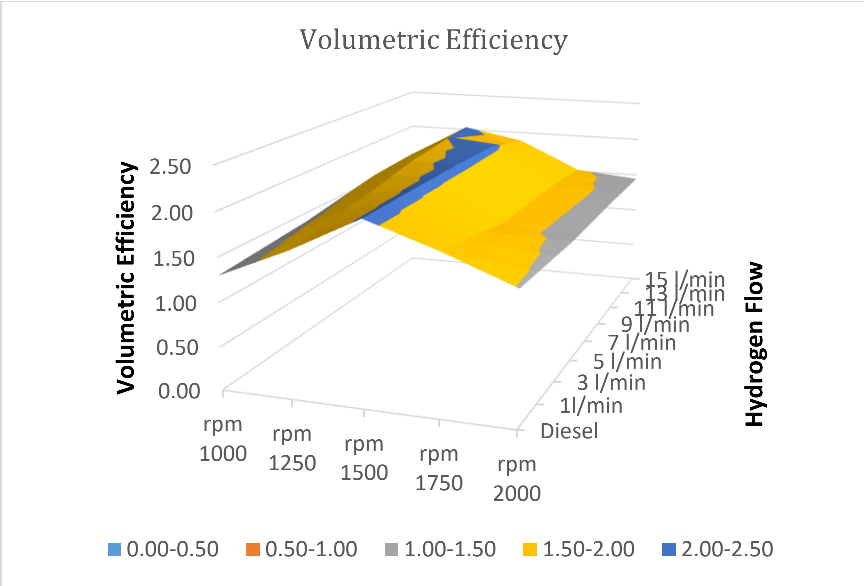
2.4.2. Volumetric efficiency (ηV)

The volumetric efficiency (ηV) is a crucial parameter in the design and analysis of internal combustion engines. Table 21 shows the computed values for the volumetric efficiency.

Table 21 – Volumetric Efficiency (1=100%)

		1000 rpm	1250 rpm	1500 rpm	1750 rpm	2000 rpm
Hydrogen flow (l/min)	1	1.30	1.65	2.06	1.79	1.49
	3	1.33	1.70	2.06	1.72	1.47
	5	1.36	1.75	2.06	1.65	1.45
	7	1.39	1.81	2.06	1.58	1.44
	9	1.45	1.87	2.06	1.58	1.44
	11	1.50	1.94	2.05	1.58	1.44
	13	1.55	1.97	2.05	1.58	1.45
	15	1.57	2.00	1.96	1.55	1.45

Figure 11 - Volumetric Efficiency



The experimental results shows that volumetric efficiency increased from 1000rpm to 1500rpm and then decreased up to the 2000rpm but, with the increase of hydrogen mixture, the volumetric efficiency decreases. This phenomena is caused by the lower heating value of hydrogen, that is higher than diesel fuel, leading to the decrease in volumetric efficiency and this is consistent with the observed results in Table 22 where O_2 content in exhaust gases decreased and also compared with the results of Karagoz et al. [93], meaning that the increase in hydrogen flow replaces the input air on the manifold and combustion chamber [65].

Also, since the engine running under no-load, the volumetric efficiency in greater than 1, meaning the turbocharger is compressing the intake air and force more air into the cylinders than they could draw in an aspirated version. This could be further validated in future work by installing a pressure sensor on the intake manifold and an air mass flow sensor with integrated air temperature sensor.

2.4.3. Exhaust emissions

Gaseous emissions were measured and evaluated combining the registered data. ***Table 22*** resumes the collected data for 1000rpm thru 1750rpm on 15l/min hydrogen flow, and shows the reduction for CO, CO_2, O_2 and NOx.

Table 22 – Emissions % reduction Dual-Fuel mode with 15l/min H_2, CO, CO_2, HC and NOx

	CO %vol	CO_2 %vol	O_2 %vol	HC ppm	NOx %vol

1000rpm	33%	19%	3%	7%	64%
1250rpm	33%	23%	2%	5%	82%
1500rpm	25%	13%	2%	6%	81%
1750rpm	50%	15%	5%	6%	83%
2000rpm	NA*	NA*	NA*	NA*	NA*

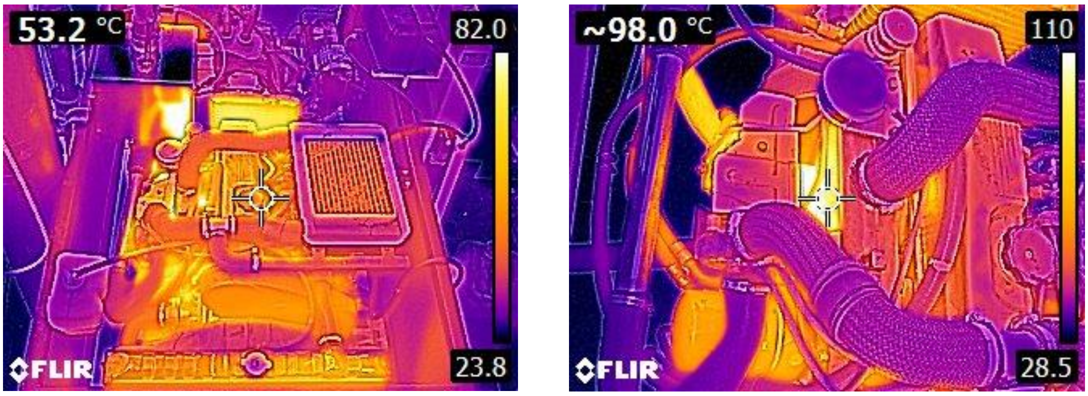
NA – Out of equipment range

As observed in ***Table 22***, there was a notorious reduction of 64-83% in NOx emissions, followed by CO with 25-50%, 33-50% in CO, 13-19% in CO_2, 5 to 7% in HC. Only oxygen had little variation in exhaust gases, <5%.

The reduction in NOx emissions can be explained since the engine was running with no load and the high volumetric efficiency observed (Table 21). Since NOx is a result of high combustion temperatures, hydrogen higher adiabatic flame temperature, higher loads in ICEs CI would mean higher NOx in exhaust gases. Nevertheless, since hydrogen flame has a higher velocity could mean, that in theory, the high temperature condition would exist for a shorter period of time. [94] It's worth emphasizing that the reduction in available oxygen, as expected due to the introduction of hydrogen into the intake manifold, can contribute to lower combustion temperatures and NOx reduction, as excess oxygen can promote NOx formation [94]. The reduction in carbon monoxide (CO) and carbon dioxide (CO_2) emissions (25-50% for CO and 13-19% for CO_2) can be attributed to the cleaner-burning characteristics of hydrogen. Hydrogen combustion produces fewer carbon-containing compounds compared to diesel, leading to lower CO and CO_2 emissions. It was also registered an average reduction in 50 % opacity for low rpms and for higher rpms the opacity was 0.01.

The ICE thermostat was set at ≈75^{0}C and it was observed that the engines overall temperature increased with increasing hydrogen flow but within engines limits. ICE temperatures were monitored with a FLIR thermal imaging camera, and it wasn't observed any overheating (***Figure 12***).

Figure 12 - Thermal imaging at 1500rpm. (a) no H_2, (b) 15 l/min H_2



(a) (b)

HC emissions in the exhaust gases, means that not all the hydrocarbons in the diesel fuel have been completely burned during combustion. HC emissions can result from various factors, including incomplete combustion, inefficient mixing of air and fuel and the absence of an EGR [94].

CONCLUSION

This study aimed to investigate the impact of dual fuel combustion, specifically the combination of diesel and hydrogen (Diesel + H_2), on the performance of a conventional Compression Ignition (CI) engine traditionally powered by fossil diesel. The research focused on key parameters including engine operating characteristics and emissions analysis under no load conditions, which cannot be generalized for real-world scenarios.

Fuel Efficiency: The research revealed a significant variation in fuel efficiency with changing levels of hydrogen and engine speed (rpm). The addition of hydrogen influenced fuel economy, with the percentage change ranging from 6.2% to 28.2% depending on the engine's rpm. However, the impact of hydrogen on fuel efficiency was not consistent across all rpm levels. At lower rpm, the engine experienced misfires and incomplete combustion when hydrogen levels were increased, resulting in reduced fuel efficiency. At higher rpm, the positive impact of hydrogen on fuel efficiency became more prominent.

This fluctuation suggests that achieving the optimal balance between diesel and hydrogen is crucial for fuel efficiency in dual-fuel diesel-hydrogen engines. Calibrating the engine's parameters to maintain the desired hydrogen-to-diesel ratio at different operating conditions is essential to maximize performance.

Volumetric Efficiency: The study also evaluated the volumetric efficiency (ηV) of the engine, which measures the effectiveness of air intake into the cylinders compared to the theoretical air volume. Volumetric efficiency is a critical parameter as it directly affects engine power output. The results indicated that volumetric efficiency increased from 1000 rpm to 1500 rpm and then decreased as the rpm increased further. Importantly, the addition of hydrogen led to a decrease in volumetric efficiency. This phenomenon is primarily attributed to the higher heating value of hydrogen compared to diesel fuel, which results in hydrogen replacing the input air in the manifold and combustion chamber.

Moreover, the study observed that the engine's volumetric efficiency exceeded 100%, indicating that the turbocharger was compressing the intake air and forcing more air into the cylinders than they could aspirate in an aspirated engine.

Exhaust Emissions: Overall, the introduction of hydrogen into the combustion process in dual-fuel mode appears to have a positive impact on emissions, particularly in terms of NOx reduction, which aligns with the environmental benefits of hydrogen as a cleaner-burning fuel. However, these findings are based on testing under no load, and the behavior of the engine may differ under varying loads and operating conditions. Further research and testing under different scenarios would provide a more comprehensive understanding of the engine's performance and emissions in dual-fuel mode.

In conclusion, this research represents a significant step towards comprehending the potential benefits and challenges associated with dual fuel combustion in CI engines, specifically the combination of diesel and hydrogen. The findings underscore the importance of precise calibration and parameter adjustment in dual-fuel systems to achieve optimal performance and emissions characteristics. This study contributes valuable insights for the development of more efficient, cleaner-burning, and environmentally responsible internal combustion engines that align with global sustainability goals.

Future work

While this study provides valuable insights into engine behavior in a no-load setting, further research is needed to enhance the understanding of dual-fuel combustion engines. Future work should include testing with a dynamometer, allowing for controlled load conditions, accurate measurements of power and torque, and simulation of real-world scenarios. Additionally, the investigation should extend to parameters such as engine efficiency, power output, torque, combustion stability, hydrogen ignition delay, and heat release rates, providing a more comprehensive evaluation of engine performance and emissions under varying conditions.

In addition to the technical aspects explored in this study, it is imperative to conduct a comprehensive economic analysis to assess the feasibility and cost-effectiveness of implementing the hybrid combustion system in current ICEs utilizing both diesel and hydrogen fuels. This economic study should include the CAPEX associated with the installation of this system in industrial machinery. Furthermore, it should take into consideration the anticipated hydrogen costs in the coming years, accounting for factors such as production methods, infrastructure development, and market trends. By examining the economic viability of this technology, it's possible to gain insights into its long-term sustainability and attractiveness to NRMM and other potential adopters in various industries.

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