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HYDROGEN AND INTERNAL COMBUSTION ENGINES – STATUS, PERSPECTIVES AND CHALLENGES IN PROVIDING HIGH EFFICIENCY AND CO_2 FREE POWERTRAIN FOR FUTURE

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REVIEW ARTICLE

ABSTRACT: Hydrogen as a fuel for internal combustion engines (ICEs) presents a promising pathway towards achieving high-efficiency, carbon-free powertrains for future mobility. This paper explores the current status, potential, and challenges associated with hydrogen-powered internal combustion engines. Hydrogen combustion offers substantial reductions in CO_2 emissions, but challenges persist, including NOx emissions, combustion stability, and the development of a comprehensive hydrogen infrastructure. The analysis delves into hydrogen's unique combustion properties, which differ from traditional fuels and require advanced engine designs and innovative combustion strategies to optimise efficiency. Additionally, the paper evaluates the environmental implications, emphasising the role hydrogen ICEs could play in achieving the ambitious targets of the Paris Agreement and the European Green Deal. Although hydrogen ICEs present a promising alternative, their success depends on overcoming significant technological and economic barriers, as well as aligning with evolving regulatory frameworks. The research concludes that despite the perception of ICEs becoming obsolete in Europe by 2035, hydrogen ICEs remain a viable powertrain solution, particularly for heavy-duty vehicles (HDVs), where they may outcompete fuel cells due to lower production costs and superior performance. This positions hydrogen ICEs as a critical component in global decarbonisation efforts.

KEY WORDS: *Hydrogen internal combustion engine (H_2 ICE), Carbon-neutral powertrains, H_2 ICE efficiency, H_2 ICE technology*

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MOTORI SA UNUTRAŠNJIM SAGREVANJEM NA VODONIK – STANJE, PERSPEKTIVE I IZAZOVI U OBEZBEĐENJU VISOKOEFIKASNOG POGONA BUDUĆNOSTI BEZ CO_2

REZIME: Vodonik kao gorivo za motore sa unutrašnjim sagorevanjem (ICE) predstavlja put koji obećava ka postizanju visoko efikasnih pogonskih sklopova bez ugljenika za buduću mobilnost. Ovaj rad istražuje trenutno stanje, potencijal i izazove povezane sa motorima sa unutrašnjim sagorevanjem na vodonik. Sagorevanje vodonika nudi značajno smanjenje emisije CO_2, ali izazovi i dalje postoje, uključujući emisije NOx, stabilnost sagorevanja i razvoj sveobuhvatne infrastrukture vodonika. Analiza se bavi jedinstvenim svojstvima sagorevanja vodonika, koja se razlikuju od tradicionalnih goriva i zahtevaju napredne dizajne motora i inovativne strategije sagorevanja kako bi se optimizovala efikasnost. Pored toga, rad procenjuje ekološke implikacije, naglašavajući ulogu koju ICE na vodonik mogu igrati u postizanju ambicioznih ciljeva Pariskog sporazuma i Evropskog zelenog plana. Iako ICE na vodonik predstavljaju alternativu koja obećava, njihov uspeh zavisi od prevazilaženja značajnih tehnoloških i ekonomskih barijera, kao i od usklađivanja sa evoluirajućim regulatornim okvirima. Istraživanje zaključuje da, uprkos percepciji da ICE postaju zastareli u Evropi do 2035. godine, ICE na vodonik ostaju održivo rešenje za pogonski sklop, posebno za teška vozila (HDVs), gde mogu nadmašiti gorivne ćelije zbog nižih troškova proizvodnje i superiornih performansi. Ovo pozicionira ICE na vodonik kao ključnu komponentu u globalnim naporima za ugljeničnu neutralnost.

KLJUČNE REČI: *Motor sa unutrašnjim sagorevanjem na vodonik (H_2 ICE), ugljenično neutralni pogoni, efikasnost H_2 ICE, H_2 ICE tehnologija*

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INTRODUCTION

Internal combustion engines have been driving the industry for more than a century. Powered mainly by fossil fuels and thus responsible for having a significant part in carbon dioxide emissions, within the global warming phenomena, the IC engine became a severely targeted technology as "obsolete", "dirty", and almost publicly sentenced to death.

So, how did we get here, and is there a stronghold for such claims? Is the hydrogen-fueled ICE only a hype or a viable solution that will provide ICE technology not only prolonged life but also a key role in decarbonising the future?

Global warming, characterised by the long-term rise in Earth's average surface temperature, has become a defining challenge of our time. Since the late 19th century, the planet's average surface temperature has risen by approximately 1.2°C, with most of this increase occurring in the past 40 years [1]. Processes driving the Earth's climate are rather complex, and neither of the models can explain the current state without large margins of uncertainty for numerous reasons. The same applies even more when predicting the future state of the Earth's climate.

In order to provide policymakers worldwide with the most relevant and regular scientific assessments on the current state of knowledge about climate change, United Nations Environment Programme (UNEPE) and World Meteorological Organization (WMO) established the IPCC (The Intergovernmental Panel on Climate Change) in 1988. In the First Assessment Report (FAR) of IPCC from 1990, greenhouse gases, particularly the rise of the carbon dioxide (CO_2) content in the Earth's atmosphere, were identified as major contributors to climate change [2]. During the next thirty years, overall, six assessment reports contributed to a better understanding of climate change and gathered the vast majority of the global scientific community around the consensus that the rise of global surface temperature is highly correlated to the rise of carbon dioxide (CO_2) content in the atmosphere [3].

The analysis of the air bubbles trapped in the ice cores drilled from the Antarctic ice sheets older than a million years [4], provided substantial proof that the amount of CO_2 suddenly started to rise at the end of 19^{th} century [5]. Moreover, the rise of the CO_2 level is stable and even accelerating, achieving current values that are more than 140% larger than the highest values in the past millennia [6]. It is a joint scientific standing that the rise of CO_2 is the most responsible for global warming due to the well-known greenhouse effect and that the rise correlates with intensive industrial activities and usage of fossil (carbon-based) fuels, i.e., that climate change is anthropogenic [3]. Greenhouse gases generally absorb and re-emit thermal (infrared) radiation and have a "blanketing" effect. Besides carbon dioxide, methane, nitrous oxide, ozone, and water vapour are also gases with significant greenhouse effect potential. In the current climate, for average all-sky conditions, water vapour is estimated to account for 50%, carbon dioxide 19%, ozone 4%, and other gases 3%, while clouds make up about 24% of the greenhouse effect [7].

The stated theory (on dominant anthropogenic causes of global warming by a massive release of CO_2 during the past 150 years) is still without sound challenge, although there are standings with claims that there are other significant phenomena that could be much more responsible for the Earth's temperature rise. One of them is that the increased presence of water vapour in the atmosphere, provoked by increased solar irradiation, is the leading cause of the intensive greenhouse effect [8]. Climate scientists soundly oppose these claims, explaining that water vapour has a minor effect on long-term global temperature change since its presence in the gaseous form in the atmosphere is relatively short. The abovementioned attitude of scepticism is also in opposition to a standard and well-established theory that increased atmospheric water vapour content, although highly involved in the overall greenhouse effect, is directly caused by the elevated level of greenhouse gases, i.e. that the increase of the water vapour content in the atmosphere is only a positive feedback of raised temperature mainly due to CO_2 increase. Some scientists focus on the long-term scale effects and changes of the Earth's Solar irradiation by the in-depth analysis of the Solar activity cycle [9] and Earth-to-Sun distance variations caused by so-called Sun Inertial motion, with a theory that the changes in the Earth's Solar irradiation contribute to a temperature increase even up to 80% (relative to the greenhouse effect itself) [10]. The predictions derived from this theory are much less alarming than those from IPCC Assessment Reports, claiming that the global temperature will drop and be well below what the IPCC predicted by the year 2053. This point of view is also under heavy criticism as a sceptic one [11].

All in all, knowledge on climate change gathered in IPCC Assessment reports, built upon a vast of various data sources and scientific expertise, became the core source of the guidelines for policymakers worldwide in defining strategies and decisions on how to fight climate change and prevent heavy consequences for the humanity which will follow by not acting. All these efforts provided essential material for governments to draw in the run-up adoption of the Kyoto Protocol in 1997, which further focused on measures and actions for limiting warming to 2°C toward the Paris Agreement in 2015. as a legally binding international treaty on climate change adopted by 196 Parties [12]. Although 2°C seems like a minor difference, the consequences of such a rise at a global level are immense. We are already seeing devastating consequences at the current level of temperature rise, including more frequent and severe heatwaves, droughts, and storms. All of this would escalate with higher temperatures rising even more, resulting in the loss of ecosystems and biodiversity on an unprecedented scale.

One of the critical measures defined as a measure for slowing down the increase of the CO_2 content in the atmosphere is related to a significant decrease in the usage of fossil fuels, i.e. limiting the overall emission of CO_2. This further implies a plan of action that will vastly increase the energy production capacities from renewable sources and emphasise the so-called carbon-neutral technologies that will provide CO_2 zero balance in their exploitation.

In December 2019, the European Union embarked on an ambitious journey to tackle climate change and environmental degradation by introducing the European Green Deal [13]. As the world grapples with the intensifying effects of global warming, the EU has taken a decisive stance with a comprehensive strategy to transform the continent into the first carbon-neutral economy by 2050. The EU Green Deal is more than just a climate policy; it's a roadmap for transforming Europe's economy to meet environmental challenges while fostering innovation and sustainable growth. At its core, the Green Deal seeks to reduce net greenhouse gas emissions by at least 55% by 2030 (compared to 1990) and reach net-zero emissions by 2050. This decarbonisation strategy spans multiple sectors, including energy, transport, agriculture, and industry.

1 PAVING THE WAY TO A CARBON-NEUTRAL FUTURE

According to the European Environment Agency (EEA), the EU's greenhouse gas emissions have already decreased by 31% between 1990 and 2021, driven mainly by a shift to renewables and improved energy efficiency [14]. However, reaching the 55% reduction target by 2030 requires even bolder actions and accelerated progress.

1.1 Cutting CO_2 Emissions: Key Measures and Strategies

One of the cornerstones of the Green Deal is the reduction of CO_2 emissions, which account for the majority of the greenhouse gas output. The European Union is implementing several measures to achieve this goal [15]:

1.1.1 Expansion of Renewable Energy Sources

Renewable energy is central to the Green Deal, with the EU aiming for renewables to account for 40% of total energy consumption by 2030. The shift from fossil fuels to wind, solar, and hydroelectric power is expected to drastically cut carbon emissions across member states. In 2022, renewables already accounted for more than 22% of the EU's energy mix, marking a significant step toward this target heading.

1.1.2 Carbon Pricing and the Emissions Trading System (ETS)

The EU's Emissions Trading System (ETS) remains one of its most effective tools for reducing carbon emissions. The ETS works on a "cap-and-trade" principle, setting a limit on total emissions while allowing companies to buy and sell emission allowances. Over time, the cap is reduced, pushing industries to invest in cleaner technologies. The recent reform of the ETS is designed to align it with the 2030 climate targets, with a more stringent cap and the inclusion of additional sectors such as maritime transport.

1.1.3 Energy Efficiency Improvements

Improving energy efficiency is crucial for reducing carbon emissions, and the Green Deal includes a "Renovation Wave" initiative aimed at doubling the renovation rate of buildings over the next decade. Buildings account for nearly 40% of the EU's energy consumption and 36% of CO_2 emissions. By enhancing insulation, upgrading heating systems, and installing smart energy management technologies, the EU hopes to significantly reduce emissions in this sector.

1.1.4 Decarbonizing Industry

The EU Green Deal emphasises the need to transition energy-intensive industries like steel, cement, and chemicals toward cleaner processes. The development of hydrogen as a key energy carrier and the deployment of carbon capture and storage (CCS) technologies are central to this effort. The EU's Hydrogen Strategy aims to establish hydrogen as a cornerstone of a decarbonised energy system, potentially reducing industrial CO2 emissions by up to 80%.

1.1.5 Sustainable Transport and Mobility

The transport sector is responsible for nearly a quarter of the EU's greenhouse gas emissions. The Green Deal targets a 90% reduction in transport-related emissions by 2050. This will be achieved by promoting electric vehicles, expanding high-speed rail networks, and introducing stricter CO_2 standards for passenger cars and Light and Heavy-duty vehicles. By 2030, the EU aims to have at least 30 million zero-emission vehicles on its roads.

1.2 Powertrains for the carbon-neutral society

Road transportation has one of the most significant impacts on total CO_2 emissions in the EU, amounting to approximately 24% (for 2020) [16]. More than 62% of that amount is emitted from Light-duty vehicles (LDVs -passenger cars and vans), while almost 25% is sourced by Heavy-duty vehicles (HDVs - trucks and buses).

With that in mind, the Green Deal agenda brought a set of regulations for restricting CO_2 emissions from vehicles:

- Regulation (EU) 2019/631 sets binding CO_2 emission targets for LDVs. It is updated in April 2023 to align the targets with the EU's 2030 and 2050 climate objectives. The ultimate goal of this regulation is the EU fleet-wide CO_2 emission target for LDVs of 0 g CO_2/km from the year 2035 onwards, corresponding to a 100% reduction [17].
- Regulation (EU) 2019/1242 sets binding CO_2 emission targets for HDVs. It is amended in 2024. by Regulation (EU) 2024/1610 [18] (as a part of the "Fit for 55" legislative package [19]) in order to broaden the scope and cover nearly all emissions from HDVs and applies to medium and heavy lorries, city buses, coaches and trailers. Revised targets are more ambitious, aiming to increase CO_2 emission reductions to 90% by 2040.

Since the vast majority of powertrains in both LD and HDVs are based on Internal Combustion Engines (ICE) fueled by fossil fuels, both regulations are aimed toward the heavy reduction of CO_2 emission from an ICE combustion process. This means the current EU "plan" is to establish the electrical powertrain as the only viable option in LDVs after 2035 and as a dominant option in HDVs beyond 2040. In order to achieve such an ambitious goal, two primary prerequisites must be achieved: Significant enlargement and optimisation of electric energy production capacities from renewable sources for the energy supply of such a massive fleet of electric vehicles (EVs) and advancements and innovations in the EVs design and production to make them affordable and available in needed numbers.

The increase in available renewable energy sources is planned to be achieved through the Renewable Energy Directive, which sets an overall renewable energy target of at least 42.5% binding (from 22% in 2022) at EU level by 2030 [20].

1.2.1 Electric Vehicles (EV)

Electric powertrain-based vehicle production and usage have been on the rise for years already, with all accompanying problems. The on-vehicle electricity could be stored primarily in batteries, supercapacitors, or a combination of two (hybrid batteries). Besides battery electric vehicles (BEVs), Plug-in hybrid vehicles (PHEVs) are also considered EVs. Although the technology of batteries is advancing, the battery modules are still bulky and heavy, giving the EVs a high mass and limited range compared to ICE-powered vehicles. The growing need to enlarge the electric charger network is still in demand and an obstacle to achieving comfortable and short charging times (comparable to ICE-powered vehicles). The EV prices are relatively high, mainly due to the high costs of a modest production scale. Despite all the problems, the number of newly registered Light-duty EVs has risen to a current share of 2.8%, with BEVs holding only 1.6% [21], where the rise strongly depends on the initial incentives and tax benefits.

In heavy-duty vehicles, the most intensive transformation is taking place in the city's public transportation fleet, where the EU yearly purchases of new BEV buses overtook diesel by numbers in 2023, with a share of 36%. The overall share of the BEV buses in the EU city public transportation fleet is at a level of 8.3% with a goal to reach zero-emission buses of 30% by 2030.

1.2.2 Alternative zero-emission powertrains

The goal of drastically cutting CO_2 emissions is built around the substantial buildup of electrical energy production capacities from renewable sources – primarily wind and solar energy. Being unpredictable and variable by nature, renewable sources-based energy production capacities require an accompanying energy buffer infrastructure, which can accumulate the energy in production peaks, thus enhancing longer-term stable availability. Multiple technologies are available for that, but each has advantages and drawbacks - from a very efficient pumped storage hydropower system via massive battery storage systems to systems that convert electricity to a gaseous or liquid fuel as energy storage.

The latter is an option with multiple potentials which will play a significant role in the overall decarbonisation process. One of the technologies that will be massively employed is the production of hydrogen from renewable energy sources based on electricity, i.e., hydrogen is considered to be the equally important energy carrier of electricity itself.

Moreover, renewable energy resources are unevenly distributed across the world. In a system reliant on renewable energy, hydrogen will serve as the energy carrier that can be efficiently transported and stored, enabling the delivery of renewable energy from resource-rich remote areas to where and when it is needed to meet energy demand [22].

From that point of view, powertrains using hydrogen as a fuel will find a significant place in building carbon-neutral industrial environments. One of the technologies already part of the decarbonisation process is fuel cell technology. It is very suitable for using gaseous hydrogen as a fuel for the direct and high-efficiency production of electrical energy. Several manufacturers are already offering passenger car models with fuel cell powertrains (Toyota Mirai and Hyundai Nexo). Although the number sold is modest, these vehicles entered the market as technology demonstrators and have been there for years, so much real-world experience is gathered.

Fuel cell powertrains are basically electrical and need relatively small battery capacities (only as a buffer) compared to BEVs. The main advantages of fuel cell technologies over BEVs are much less needed battery capacities and thus smaller system mass and much shorter "charging" times.

Fuel cell cars use onboard tanks with gaseous hydrogen stored at 700 bar with approximately 5 kg capacity (0.04 kg/l). Remarkable efficiency enables these vehicles to have an economy of 0.8-1 kg H2/ 100 km, giving them a range usually higher than in BEVs and closer to ICE-based vehicles. Besides, the hydrogen filling time is within the range of 5 minutes (in optimal conditions), making this technology more convenient and closer to the comfort of usage offered by ICE-based vehicles.

Fuel cell technology is also present in Heavy-duty vehicles – mostly in city public transportation buses. The fuel cell technology application in city buses offers more attractive performance than battery-based solutions (less weight, higher range and shorter fueling time). Although the presence of fuel cell-powered buses is still modest, the interest and number of orders are growing. For example, the biggest ever one-off contract in Europe for the delivery of fuel-cell-powered buses for an order of 130 buses was signed recently [23].

As a viable option for converting electricity to usable fuel (so-called e-fuel), technologies are available for synthesising carbon-based fuels from captured CO_2 (from some industrial processes) and hydrogen produced from renewable energy sources. A variety of synthetic fuels can be produced, like higher alcohols, ethers, and synthetic hydrocarbons (synthetic gasoline, paraffinic diesel, and paraffinic kerosene) [24], [25].

1.2.3 Internal combustion Engines-based powertrains?

The overall impression of introductory facts and trends could imply a conclusion that, within the Green Deal agenda, there is no more space for a powertrain technology, which has carried the industry on its shoulders for over a century – Internal Combustion Engines. Is it so?

Hydrogen

Legislative requirements and CO_2 *emission*

It is well known that ICE can use hydrogen as a fuel, thus providing water vapour as a dominant exhaust product. From that point of view, ICE is conforming to the future demands of zero CO_2 emission – at least according to currently defined and valid test and approval methodologies (Euro VI / post Euro VI legislative requirements). Hydrogen-powered ICE (H2ICE) technology appears very competitive to the Fuel cell technology, although with a few drawbacks on the ICE side:

- Due to the high-temperature combustion of hydrogen with atmospheric air, NOx emission is also present as an exhaust gas component. So, from that point of view, H2 ICE, inherently, is not an absolutely zero-emission powertrain unless an efficient Selective Catalytic Reduction system is implemented as a part of the engine's exhaust after-treatment system. Also, if the current SCR technology (used in Diesel ICEs) is foreseen as a technology for the future hydrogen ICE, with urea as a reductant, the SCR system generates a very small amount of CO_2.
- Due to an unavoidable lubrication system, ICE operation is regularly followed by some oil consumption toward the combustion space, i.e., some oil combusts and generates non-zero CO_2 emission.

It is still unclear how exhaust emissions from H2 ICE will be treated. The future legislation basis for the H_2 ICE is currently under discussion, with an initial "lean" approach to encourage further developments and investments in H2 ICE technology [26], [27]. The current approach suggests that the H2 ICE emission will be treated similarly to conventional ICE, which means that the focus will be given to NOx emission and that the SCR system will be mandatory for H2 ICE.

Simulation of a long-haul heavy-duty application in the VECTO long-haul duty cycle shows that the CO_2 emission of the conventional diesel powertrain is 604 g/kWh. When the powertrain is replaced with H2 ICE, the CO_2 emission reduction is 100% if the emission from the urea-based SCR system is not considered. If this CO_2 emission is also taken into account (5 g/kWh), the overall reduction of CO_2 is still more than 99% [28].

Total Cost of Ownership (TCO)

Real-world experience shows that fundamental economic indicators drive market response and purchasing decisions. Fuel cell based powertrains CAPEX is higher due to a higher cost of the Fuel-cell specific power (approximately 3 x of H2 ICE). On the other hand, available data on maintenance costs are not consistent or completely coherent. Some analyses are based on maintenance costs of the fuel cell-based truck estimations, which are lower than those of ICE counterparts [29]. Others are relying on more realistic projections [30] or real-world experience, particularly from USA operators who have been in the maintenance business with fuel cell powered busses for years, delivering conclusions that hydrogen fleet maintenance is 20-125% more expensive than diesel fleet [31]. In both approaches, having in mind even the fact that the efficiency of the H2 ICE is lower (7 or more %), the conclusion is that the TCO of a Fuel cell truck is at least comparable but most likely considerably higher than those of the H2 ICE based truck. Not to mention that although the fuel cell technology has been present on the market for decades, the lifetime of the fuel cells is much shorter than those of potential H2 ICE. For example, claims for the latest generation of fuel cells lifetime for heavy-duty vehicle applications are 25000 hours [32], which implies that at least one (lifespan midterm) replacement is needed with a new power stack.

Therefore, H2 ICE has a lot of the potential to be TCO competitive, particularly if further progress is made in the area of H2 ICE combustion process research towards high efficiency.

"Zero-impact" for OEMs / truck makers

All truck manufacturers have established expertise with conventional ICE powertrains. They employ skilled professionals, and their systems are well-understood and optimised. Any modifications would be relatively minor compared to alternative approaches. Additionally, the impact on powertrain production would be minimal, as would the necessary changes to the supply chain. The hydrogen tank system would clearly introduce new requirements for vehicle integration and service operations. However, other components are already well understood, their behaviour is predictable, and the expert teams are already available to address any issues.

Alternative CO_2-neutral fuels

Besides hydrogen, as a most promising fuel option for zero-emission ICE, hydrogen-carrier fuels like ammonia are also attractive as zero CO_2 emission fuels [33]. The ammonia production and process equipment industry is mature and well-established, and that is why ammonia is foreseen as an attractive zero-emission fuel for ICEs in marine transport, mainly since the fueling capacities are already available (or can be built effectively) in large ports. Due to the high power demands required by ship propulsion, it is currently hard to imagine any other technology than ICE that can provide the required performance.

It is expected that the much larger scale production of synthetic fuels will be imminent in the future, taking a substantial part in overall decarbonisation in various applications – not only as CO_2 -neutral fuels for ICE powertrains and the aviation sector but also as a means of CO_2 storage. Due to high production costs, the prices of potential synthetic fuels are much higher than those of fossil fuels. However, with the production capacities upscaling and the expected fall of input prices, synthetic fuels can be expected not only to have a role in the decarbonisation process but also to be a competitive alternative to fossil-based fuels [34].

Viable and perspective options for ICE powertrains within the Green Deal agenda?

A comparable number and quality of uncertainties affect all drive technologies. Therefore, it is unjustified to point to any of the drive technologies as absolutely preferable [35]. Regulation (EU) 2019/631 is considered to ban ICE-based powertrains in LDVs starting in 2035. However, the potential consequences of such strict goals are still discussed, and public pressure is being put on to modify the regulation toward postponing and/or including synthetic fuels as a viable carbon-neutral option [36].

On the other side, ICE can still be used as a CO_2 zero-emission powertrain if powered by hydrogen. It is a question of how the ICE technology can be comparable to other alternatives – BEVs and fuel-cell powered vehicles in the LDVs area- in terms of costs, complexity, and range/efficiency [37]. ICE Efficiency is seen as the most significant disadvantage over other hydrogen powertrain technology – the fuel cells. Considering the feasible amount of hydrogen that can be stored in passenger cars (ca 5 kg), the range is heavily influenced by powertrain efficiency. The efficiency gap between fuel cells and ICE powertrains became smaller due to ICE technology advances, which is demonstrated on highly optimised large bore engines [38]. Still, the ultra-high efficiency hydrogen-powered ICE powertrain solution applicable to LDVs is yet something in which much R&D effort must be invested to be achieved.

Therefore, a hydrogen ICE-based powertrain is not yet seen as a viable option for the future. On the other hand, if the usage of synthetic fuels in LDVs is allowed (amended regulation scenario), the ICE will stay a very attractive option for powertrains.

In the HDV area, battery electric powertrains are already used, mainly in city public transportation buses. Due to a limited range and rather long charging time, the battery electric powertrain concept seems unpractical for HD applications covering longer distances. Therefore, fuel cells are in the spotlight of media and governing policies as preferred zero-emission future powertrains, emphasising high efficiency as a critical argument. Conversely, it is well known that fuel cells achieve the highest efficiency at partial loads, which suites a highly variable working cycle of HDVs like city buses but not trucks (medium and heavy lorries), which are much longer driven on higher loads. Having in mind other abovementioned disadvantages of fuel cell powertrains (maintenance costs, lifespan, total cost of ownership,…), it appears that high-efficiency Hydrogen ICE could be the most prominent candidate as a CO_2 zero-emission powertrain of the future in the HDVs area, particularly medium and heavy trucks/lorries.

In order to “secure” the future of hydrogen ICE powertrains, the utmost importance is for R&D capacities to offer a competitive and highly efficient ICE-based powertrain solution.

2 HYDROGEN AS A FUEL

As the world shifts toward cleaner energy, hydrogen is increasingly seen as a key player in the race to decarbonise transportation. The appeal is clear: hydrogen is the most abundant element in the universe. It emits no CO_2 when burned and can be used in both ICEs and fuel cells to power vehicles. Nevertheless, despite its promise, hydrogen remains a niche fuel in the global transport sector. What makes hydrogen a unique fuel, and what challenges lie ahead in making it a widespread solution for vehicles?

2.1 Properties and challenges in the widespread adoption of hydrogen as a fuel

2.1.1 Energy density

Hydrogen (H_2) is a colourless, odourless gas. As an element with the simplest atomic structure, it has the smallest density and is more than 14 times lighter than air at the common room temperature. As a fuel, hydrogen has a high energy density per unit of weight—approximately 120 MJ/kg, almost three times that of gasoline, but due to a small density, high pressures are required to store the comparable energy in tanks applicable for vehicle use.

To be stored onboard vehicles, hydrogen must be compressed to high pressures (typically 700 or 350 bar) or liquefied at extremely low temperatures (-253°C). Both methods are energy-intensive and require robust infrastructure. Although more than 900 hydrogen refuelling stations (HRS) were installed globally by the end of 2023, much work still needs to be done to define/update numerous standards for mass worldwide use [39], [40].

2.1.2 Onboard storage and refuelling

The HRS standards cover general requirements, dispenser, dispenser-vehicle communication, mechanical connection, hydrogen quality and fuelling protocol [41]. Standards addressing the mechanical connection and refuelling protocol are paramount for achieving safe, convenient, and fast hydrogen refuelling. Standards are also categorised in terms of vehicle class since the potential amount of hydrogen to store onboard differs significantly between LDVs and HDVs. One of the refuelling speed limitations is related to a maximum gas flow from the dispenser. Mechanical connections for LDVs and buses are designed to provide a maximum flow of 60 g/s of hydrogen. During refuelling, the temperature of the in-tank gas rises; therefore, an automation system must strictly control the process to limit the maximum in-tank temperature and pressure, and this is achieved by implementing the refuelling protocol. The refuelling automation system relies on information (in-tank pressure and temperature) supplied by the vehicle to the HRS via standardised communication. Overall refuelling time varies and depends on initial conditions met in the vehicle tank, and for LDVs, a refuelling speed is approximately 1kg of hydrogen per minute. HDVs (trucks), due to a much larger tank capacity, require higher, at least doubled refuelling capacities in terms of flow and speed. Thus, a newly proposed protocol within the PRHYDE project (if standardised) should provide a refuelling speed of 80kg of hydrogen in 10 minutes [41], [42]. Similar efforts are being made in the USA to improve adequate SAE norms [43].

2.1.3 Combustive properties of hydrogen

Hydrogen is a fuel, and such has stored chemical energy. It has associated hazards, but it is no more dangerous than the other fuels that store chemical energy. It is just different, and the science behind hydrogen flammability and combustion is well-known and well-understood [44].

Table 1 Flammability Properties of Hydrogen and Other Fuels

Property		Hydrogen	Methane	Propane	Gasoline Vapor
Flammability Concentration in Air (vol%) [45]	LFL	4.0 %	5.0 %	2.1 %	1.2 %
	UFL	75.0 %	15.0 %	9.5 %	7.1 %
Most Easily Ignited Mixture in Air (vol%)		29% [46]	8.5% [47]	4% [48]	2% [49]
Adiabatic Flame Temperature [49]		2483 K	2236 K	2250 K	2289 K
Buoyancy (ratio to air)		0.07	0.54	1.52	4
MIE [50], [51]		0.011-0.017 mJ	0.28-0.30 mJ	0.25-0.26 mJ	0.8 mJ
Autoignition Temperature [49]		500 °C	580 °C	455 °C	246 – 280 °C

Hydrogen has properties which distinguish it from other widely used fuels in ICE. These impose hazards and risk concerns when used in vehicles and public transportation in general, which went through thorough analysis and checks in numerous studies on how to deal with them [52], [53]. Hydrogen is known as a gaseous fuel with the broadest range of flammability concentration limits in air - from 4.0 (LFL) to 75.0% (UFL) [45].

The hydrogen's minimum ignition energy (MIE) is an order of magnitude lower than the other fuel types, as seen in Figure 1[51]. As a result, an ignition source of an energy level far lesser than a typical automotive spark plug can be sufficient to ignite a hydrogen-air mixture in a wide concentration range – even a very lean one. Unfortunately, that also means that hot gases and hot spots on the ICE cylinder/head can serve as an ignition source, creating problems of premature ignition and flashback. Preventing this is one of the challenges of running an engine on hydrogen.

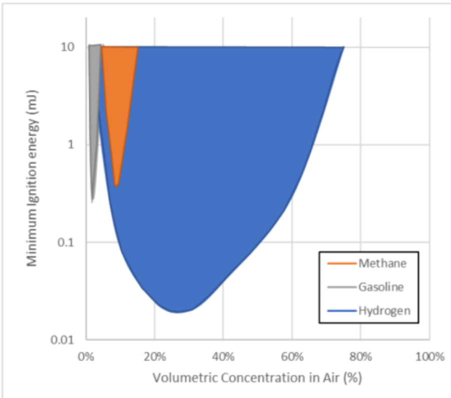

Figure 1 Minimum Ignition Energy for Different Fuels vs. Concentration [49]

Hydrogen has a shorter quenching distance compared to gasoline (0.6 mm vs. 2.0 mm), allowing hydrogen flames to approach the cylinder walls more closely before extinguishing [54]. As a result, quenching a hydrogen flame is more challenging than quenching a gasoline flame. Additionally, the shorter quenching distance increases the likelihood of backfire, as a hydrogen-air flame can more easily pass through a nearly closed intake valve compared to a hydrocarbon-air flame.

Hydrogen auto ignites at much higher temperatures than gasoline vapour, and therefore, it is considered suitable for use in ICE at higher compression ratios, which naturally have higher efficiency potential. Autoignition temperature is pressure-dependable, and it is way above 530°C (vs. 246-280°C for gasoline vapour) at pressures usually achieved in the compression stroke of an ICE [55]. The feature often promotes hydrogen as an ICE fuel that is much less prone to detonation/deflagration than gasoline, which is not quite so in real, state-of-the-art ICE applications. It is not simple to define the octane number (RON) of hydrogen since the standard ASTM procedures for determining the RON are designed for gasoline, and due to differences in combustion behaviour, these are not very usable in the case of hydrogen. Hydrogen-air mixture combustion speed and autoignition are heavily influenced by equivalence ratio, pressure and temperature, and thus, a comparison with the knocking behaviour of gasoline can be made only through modified RON-determination experiments by emphasising more comparable in-cylinder combustion conditions. When analysed from that point of view (modified RON), it appears that hydrogen has a higher octane number than gasoline (RON 93.7 @ λ=1, RON >120 @ λ=2), which is evident if hydrogen is used in typical gasoline engines with moderate compression ratios [56]. However, due to the complex relation of initial in-cylinder conditions (temperature, pressure, mixture non-homogeneities), low ignition energy and short ignition delay at higher compression ratios, hydrogen becomes a fuel considered highly prone to abnormal combustion, leading to preignition and engine knock, where the former is the most significant problem to cope with. Still, at the bottom line, despite not being knock insensitive, hydrogen can be employed as a fuel in ICE with higher compression ratios, i.e., in areas that are not reachable to gasoline, thus providing potential for reaching higher, diesel-like efficiencies.

Figure 2 presents an example of irregular hydrogen combustion in ICE. The process is captured in the ICE laboratory of the Faculty of Mechanical Engineering at the University of Belgrade during trials with specific engine configuration and λ=1.5 operation. As can be seen, combustion develops quite typically at a load of cca 8 bar IMEP without any visible "announcement" of potential combustion irregularities (Figure 2a), where the left (green) marker points to an end of injection angle and the next one (red) spark advance i.e. ignition angle. Suddenly, a late preignition occurs approximately 0.6 ms before regular spark (Figure 2b). Not being completely consumed by preignition flame, spark occurrence ignites another part of the mixture which is immediately followed by knock phenomena. This drastically rises the in-cylinder temperature providing even more favourable conditions for the preignition to appear in the following cycle. Another late preignition occurs in the upcoming cycle even closer to the TDC with an indication of a triggered volumetric combustion (Figure 2c). This further contributes to a deposited heat which in the next cycle triggers an early preignition which starts almost at the end of injection with a huge increase of the in-cylinder pressure and temperature and sharp drop of IMEP (Figure 2d). Intensive heat release sustains a sufficiently high temperature level during the compression stroke enabling successive cycles with hydrogen (early) autoignition (Figure 2e)with several overlapped successive irregular cycles with hydrogen autoignition).

Hydrogen combusts much faster than gasoline, which also contributes to the potential of enhancing ICE efficiency. Although the ignition delay rises and combustion speed drops with the enlargement of the air excess ratio, even a lean hydrogen mixture combusts at speeds comparable to gasoline. Fast combustion, even at higher air excess ratios, makes hydrogen an excellent fuel for the lean ICE operation.

Hydrogen has very high molecular diffusivity. It diffuses rapidly into the air, facilitating uniform mixture formation. In ICE with direct hydrogen injection, this property also influences the shape and range of the unignited (turbulent) jet. Combined with low density and high injection pressures, high diffusivity contributes to momentum-driven gas jets, which highly interact with all surfaces within the engine combustion chamber (cylinder head and lining, piston head) [57]. So, despite high diffusivity, this often results in a nonhomogenous mixture, which has consequences in combustion in general and, particularly, in enhancing abnormal combustion triggering mechanisms. That's why tumble-driven mixture formation is favoured even in HD engines as a concept that contributes to better mixture formation and combustion flame kernel positioning away from the cylinderwalls.

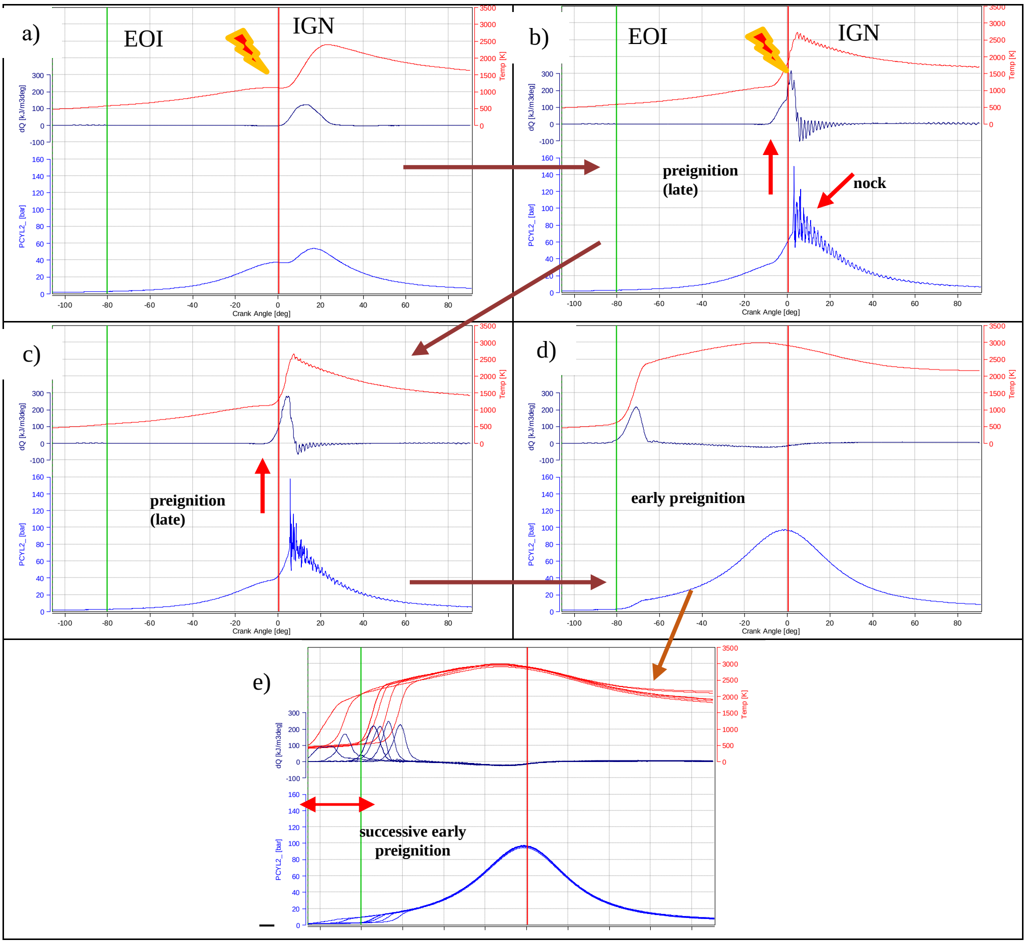

Figure 2 An example of developing irregular hydrogen combustion through four successive cycles (CR=13.7, λ=1.5, 2000 rpm, NA, IMEP≈8 bar)

2.2 Hydrogen in ICE

2.2.1 Technologies

The most significant advantage of hydrogen-fuelled IC engines is the existence of proven and well-established basis technology. Due to the specifics of the hydrogen, the well-known ICE needs some adaptation and additional R&D efforts, but all that the industry can provide in a short time with a minor modification of existing production and maintenance capacities. From that point of view, hydrogen-fuelled engines are considered a technology solution derived from existing spark-ignited (SI) or compression-ignited concepts.

Two general approaches can be used for hydrogen-air mixture formation: Low-pressure injection of the hydrogen into the intake port (PFI) and direct injection of the hydrogen into the cylinder (DI). The usage of PFI technology seems attractive and straightforward since it is implemented in many gas (CNG) engines. This approach seems adequate since the technology of high-flow, low-pressure gas injectors is mature (although not specifically for hydrogen). Using a low-pressure injection also maximises the utilisation of the pressurised hydrogen stored onboard in vehicle tanks. The most significant drawback of the MPI technology is the “easy-to-reach” condition of the flame backpropagation, as well as the occurrence of early preignition in the cylinder. Also, the MPI approach leads to a lower volumetric efficiency (considering the high hydrogen/air volumetric ratio needed even for a lean operation). Therefore, MPI technology is not seen as a pathway toward the high-efficiency hydrogen engine.

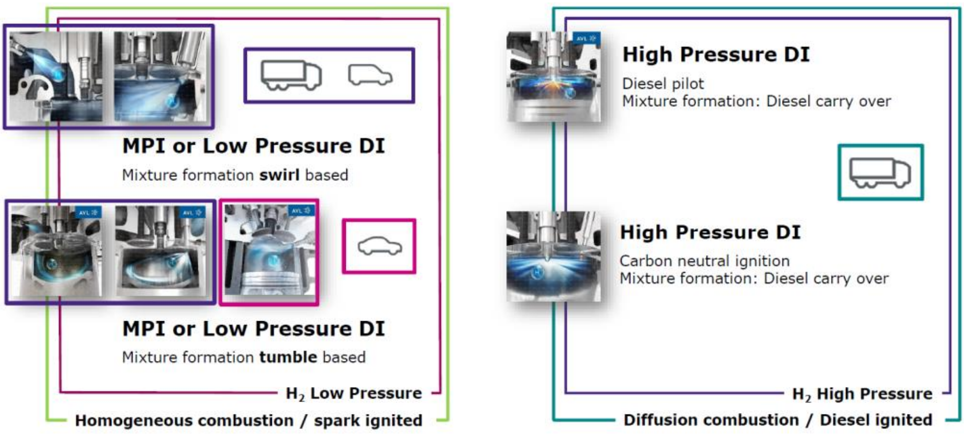

Figure 3 Hydrogen Combustion Concepts for Commercial Applications and Passenger Cars [58]

The DI approach diminishes the back flame issue and appears as a more versatile technology regarding combustion control potentials. Since the hydrogen is injected into the (already filled with air) cylinder, this approach can provide higher volumetric efficiency and, thus, higher specific power while keeping in mind that at lean operation, that can be achieved at the expense of high boosting pressures. A significant drawback of a DI approach is related to the needed capacity of the injection system since a large amount of hydrogen ought to be injected into the cylinder in a limited crankshaft angular (CA) window. Additionally, it is well-known that due to a high diffusivity, hydrogen can be absorbed by metals, which further can induce metal cracking. This hydrogen embrittlement is also an issue that must be carefully addressed when designing the hydrogen injection system, particularly injectors. Above that, hydrogen has a weak lubrication capability (even worse than CNG), which requires further mechanical development addressing friction issues toward reliable and durable injector solutions. Currently, much effort is invested in developing a new generation of both PFI and DI hydrogen injectors capable of delivering the required flow, mainly focusing on low-pressure solutions (20-30 bar) with high durability in mind [59], [60].

Low-pressure injection provides the best possible utilisation of the onboard stored hydrogen fuel. On the other side, since the injection occurs after inlet valve closure, the injection pressure has to be high enough to enable the free injection, opposing the in-cylinder pressure level reached during the compression stroke at the end of the injection. In summary, low-pressure DI has advantages but is generally limited by the necessity of delivering hydrogen through a long-duration single injection process.

Multiinjection strategies offer more versatility in controlling mixture formation, homogeneity, and combustion, which all influence and potentially enhance efficiency. Achieving this is possible by utilising higher injection pressures, i.e., with only high-pressure injection, the injection timing can be varied within a wide range, and thus, not only controlled fuel stratification can be realised but also an explicit control of the combustion process [61]. Thus, the high-pressure DI injection concept is considered one which could support combustion control concepts toward the highest possible efficiency. Although the low-pressure DI concept cannot offer as many degrees of freedom as the former, it can still provide many advantages of high-pressure while being closer to series-production readiness. That is why the low-pressure DI is the current focus of R&D.

The combustion system concept, foreseen for potential passenger cars hydrogen ICE, is based on a well-known technology used in gasoline engines – spark ignited with a pentroof combustion chamber and induced tumble air/fuel mixture motion. This concept is well-proven with hydrogen and provides, so far, the best results [62].

In the area of HDVs, currently, dominant CI diesel engines are swirl-based with a flat-top cylinder head. Current HD hydrogen-fuelled demonstrators rely on this concept to demonstrate that not-so-big changes are needed in the engine layout to “switch” them toward hydrogen use. Current R&D efforts are conducted on two tracks: One with a spark-ignited concept and another with a compression ignition to prove the highest possible efficiencies [58],[30]. Latter are actually dual-fuelled engines with a minor pilot amount of diesel fuel for stable auto-ignition of the hydrogen/air mixture [65]. Operating with a hydrogen energy ratio of 97.5% at full load, this setup meets potential CO_2 emission targets in HDVs and demonstrates an efficiency of 51.5% [66]. Also, controllable auto-ignition is demonstrated as possible with a spark plug assistance (ignition of lean pilot mixture followed by autoignition of late injected hydrogen [67]) or by means of a hot surface/glow plug [68].

a)

b)

c)

d)

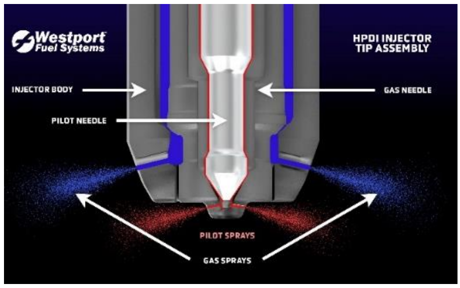

Figure 4 Hydrogen injector technologies: a) 300 bar DI injector from Hoerbiger for H2BVplus project [63];
b) low-pressure DI injector from Liebherr [64], [59]; c)-d) high-pressure HPDI hydrogen and diesel pilot injector as a single unit with injection pressures of up to 300 bar [30]

2.2.2 Combustion process control

Hydrogen is an extremely easy-to-ignite fuel with high-speed combustion. Therefore, there are two crucial aspects to deal with in order to achieve stable and controllable combustion. The first deals with a preignition, i.e., measures for its suppression. The second deals with a harsh pressure (and temperature) rise due to high-speed combustion, which further can easily lead to knock, thermal overload, extremely high in-cylinder pressures and high-pressure rise gradients challenging the mechanical integrity of the engine and causing harsh noise.

Using a stoichiometric ratio at high compression ratios gives a harsh, high-speed, and knock-provocative combustion process with the highest performance (specific power), the best transient behaviour and the highest NOx emissions. On the other side, lean combustion provides slower, much less knock-prone combustion, which is easier to handle even at high loads. Lean combustion also brings much less NOx emission and high efficiencies but with lower specific power and slower transient response as a drawback while needing much higher boost pressures for a higher load operation. So, depending on the application requirements, a mixture of approaches can be used to satisfy the stated objectives. However, in all cases, a kind of combustion moderator is needed to overcome harsh combustion behaviour on higher loads, which is not avoidable at high compression ratios and lower air excess ratios ($\lambda<2$).

One of the frequently used and discussed combustion moderators is water, which is injected through a dedicated PFI system and effectively influences the combustion speed, thus enabling stable combustion and control on higher loads even with stochiometric operation [62]. The drawback of this approach is the necessity to equip the vehicle with an additional water tank. Much research is involved in finding solutions that can avoid this, and one of the promising options is to use onboard-generated water by partially condensing engine exhaust gases. The second and largely exploited possibility is implementing the EGR concept, which significantly contributes to more stable and controllable combustion, simultaneously lowering cycle temperature and NOx emission.

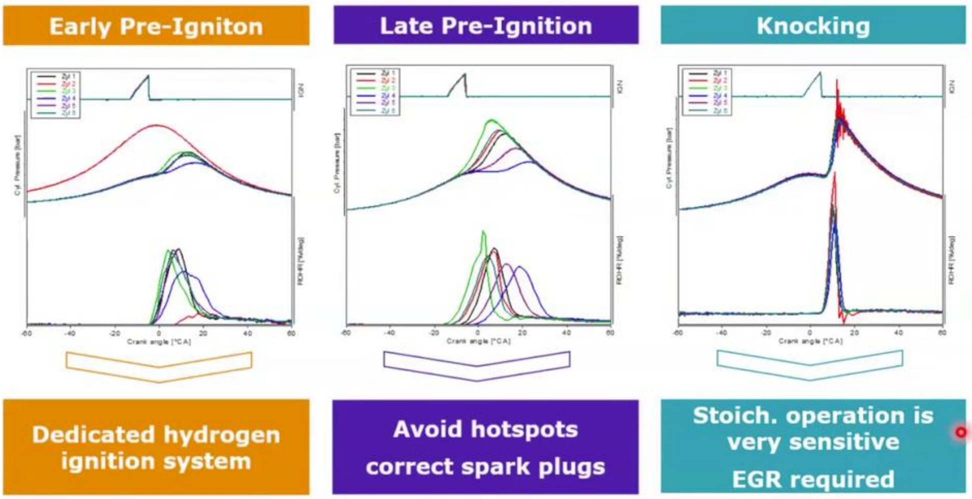

Figure 5 Hydrogen combustion anomalies - challenges in controlling hydrogen combustion process in ICE [69]

Due to the extremely low ignition energy required, special attention is given to suitable ignition systems. Spark plugs should be of highly heat conductive “cold” type and ignition coils, and their control should ensure needed spark plug electrodes potential explicitly when required, i.e. with high suppression of so-called “ghost spark phenomena” [70].

2.3 NOx emission control

The combustion of hydrogen/air mixtures inevitably leads to the formation of nitrous oxides through the well-known Zeldowich formation mechanism [71]. Highly temperature-dependable, the NOX formation rate in hydrogen engines is heavily influenced by the used air excess ratio and applied EGR.

For passenger car engines, two NOx after-treatment system options are considered as a potential solution for minimising tailpipe NOx emission. The so-called passive SCR (selective catalytic reduction) is a viable engine aftertreatment system (EAS) option for stoichiometric operation (Figure 6a). This concept features onboard ammonia (NH3) generation, formed in the three-way catalytic converter (TWC), closely coupled to the engine, which is then used as a reduction agent in a remotely placed (underfloor) SCR with or w/o additional external air [72], [73]. A conventional SCR system is needed for lean operation with an active SCR operation with a close coupled oxidation catalyst and SCR with active urea dosing (Figure 6b) [58].

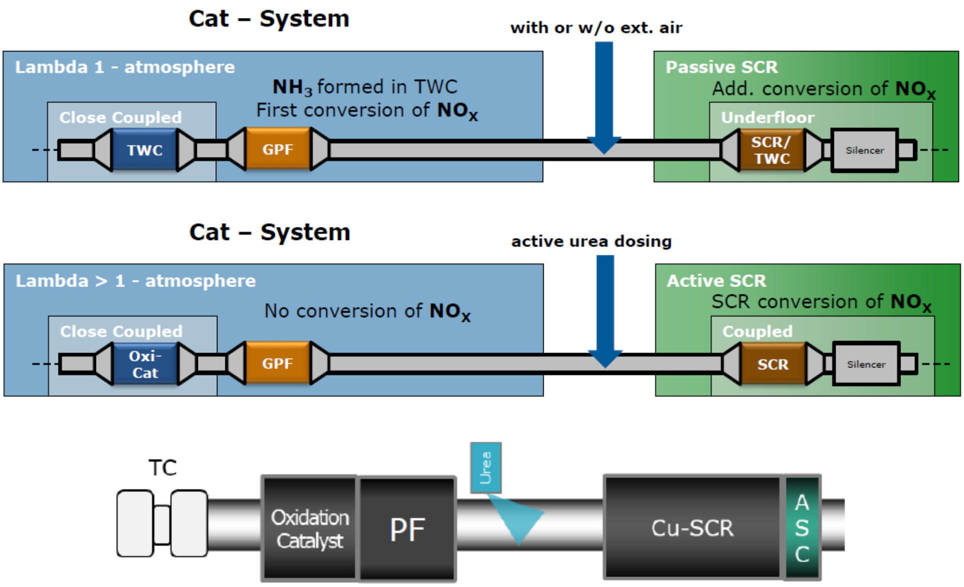

Figure 6 Exhaust aftertreatment systems layouts suitable for hydrogen ICE and fulfilment of Euro VI norms [58]

Foreseen EAS concepts for hydrogen HDVs are currently built with Euro VI norms in mind. The already tested and proven layout is a diesel-like concept and consists of an oxidation catalyst, an active SCR with a copper-based catalyst and an ammonia slip catalyst at the end (Figure 6c) [58]. Recently adopted EURO VII norms put further restrictions on NOx emissions, but it is considered that a two-stage SCR system is capable of providing the required performance in reducing NOx emissions below new limits [74].

3 H_2 ICE DEMONSTRATORS

R&D on hydrogen ICE has been conducted for decades, with its ups and downs, driven chiefly by the interests of its time. Much knowledge has been accumulated over time, and numerous examples of IC engines converted to hydrogen ICE are used as technology and various concept demonstrators [75], [76]. A significant milestone in hydrogen ICE development was the Hydrogen 7 project by BMW [77], [78]. It was the first hydrogen ICE vehicle produced in numbers sufficient to be used as a worldwide demonstrator. Hydrogen 7 car was powered by V12 6 litre bi-fuel engine with both hydrogen and gasoline tank onboard to achieve the highest possible range. The interesting aspect of the design is the choice and trial of liquid hydrogen storage as a measure for achieving an onboard mass of stored hydrogen fuel as large as possible. Having almost twice the volumetric density (0.071 kg/l for liquid H2 vs. 0.04 kg/l for gaseous H2 @ 700 bar), storing the hydrogen in liquid form seems a reasonable step for enhancing the capacity of onboard fuel storage and thus range. Unfortunately, hydrogen has to be cooled to at least -253°C to be kept in a liquid form since hydrogen boils off at a temperature above that limit -therefore, the storage tank has to be insulated (vacuum). Despite insulation, a heat transfer is unavoidable. This leads to permanent fuel boil-off, which must be vented to limit in-tank pressure buildup since the cryo tanks are low-pressure vessels. As an early hydrogen ICE demonstrator, the engine fueling system was built on many compromises. A PFI injection system was implemented, which mainly influenced the engine's volumetric efficiency and cut the gasoline "original" performance by more than 40%. The injection pressure was built by heating and evaporating the liquid fuel in a heat exchanger and thus kept at a level comparable to the gasoline PFI system (cca 3 bar). The original engine's compression ratio was lowered from 11.3 to 9.5. Furthermore, to avoid complex aftertreatment of the exhaust NOx, the control strategy was focused on using air excess ratios, which minimise the NOx generation. Thus, for "high power" operation, an air excess ratio of λ=0.97 was used since a slightly rich mixture provided a neglectable amount of NOx entirely handled by TWC with only a 0.1% hydrogen slip. An excess ratio of λ>1.8 was also used for part loads to minimise NOX emission [79]. Mixtures with 0.97<λ<1.8 were avoided entirely as a range where NOx emission was substantial and could not be diminished by TWC. The concept was designed to demonstrate the capability to fulfil SULEV norms completely, and it proved successful despite its shortcomings – relatively low engine efficiency and fuel los due to boil-off.

At the same a larger-scale project HyICE was conducted in the EU [61]. An integrated project within the sixth framework of the European Commission gathered several key industry players around a quest to explore the possibilities and perspectives of hydrogen ICE and its optimisation. The project identified hydrogen direct injection as the most prospective concept. An efficiency of 42% was demonstrated on a specially built single-cylinder research engine with diesel-like geometry and injection pressures of 300 bars [80]. The concept was further explored within the H2BVplus project with experiments employing hydrogen self-ignition [63], [68]. The potentials of the low-pressure direct injection were also explored through a dedicated hydrogen ICE design and injector nozzles optimisation, which provided a 12.8-litre engine with a maximum power output of 200kW and an effective efficiency of 42%. This engine (MAN typ H2876 UH) is further tested in public transportation within the HyFLEET: CUTE project [81]. The HyICE also explored the concept of cryogenic port injection (CPI) - an injection of liquid hydrogen with a specially designed injector. CPI concept demonstrated a potential for the increase of specific power by 25% and providing performance comparable to a gasoline PFI engine but with substantially expanded range of good efficiency where 44% is demonstrated with increased compression ratio.

Both projects mentioned were conducted more than 15 years ago but brought to the engineering community a significant knowledgebase. In the meantime, ICE technology has advanced mainly in applying advanced mechatronic systems in the control of mixture formation and combustion process control. AVL presents one of the most recent examples of H2 ICE demonstrators, with two H2 ICE demonstration platforms, by following the in-the-meantime built general opinion and projections of the H2 ICE implementation in the future automotive technology.

According to all presented technology facts, current developments and EU policies, it is obvious that European automotive manufacturers do not see H2 ICE as a powertrain solution for passenger cars at the moment, mainly due to limited options for storing needed amounts of hydrogen onboard for a range comparable to a fuel cell or even battery electric vehicle. As a manufacturer that invested more than 40 years of R&D in H2 ICE, even BMW is abandoning the H2 ICE idea in cars and orienting itself toward fuel cell-based powertrains [82]. Supporting argument for this decision also lies in the fact that, as being electric, the majority of components of the fuel cell-based platform are compatible with the platform of battery electric vehicles, which are foreseen as a future of car production in Europe.

An exemption in the H2 ICE powertrain for cars is seen in racing sports. Therefore, AVL recently introduced a demonstrator of an H2 IC racing engine of remarkable performance: 300 kW @ 6500 rpm and 500 Nm @ 3000-4000 rpm from a two-litre four-cylinder inline engine. The concept proved the viability of a power density of 150 kW/litre and BMEP (break mean effective pressure) in a range of 32 bars.

Several concepts could be considered as potential H2 ICE operation concepts:

- Pure lean concept
- Lean + EGR
- Stochiomteric + combustion moderator

The pure lean concept relies on λ≈2.5 to achieve the lowest NOx emission. A drawback of a lean operation is the requirement for very high boost pressures to reach high power and the necessity of NOx aftertreatment with or without SCR. By introducing EGR, it is possible to slightly reduce boosting pressure with joint reduction of NOx, but NOx aftertreatment with or without SCR remains a requirement. Stoichiometric operations provide the highest power, but the combustion is very prone to irregularities, and thus, some combustion moderator is required to put the combustion process in stable control. Also, NOx emission at λ=1 can be handled with TWC. Therefore, AVL chose to use λ=1 operation with water as a combustion moderator (injected through a dedicated PFI system). AVL's H2 racing ICE has endured testing and is currently under analysis for further improvements in all possible aspects (***Figure 7***).

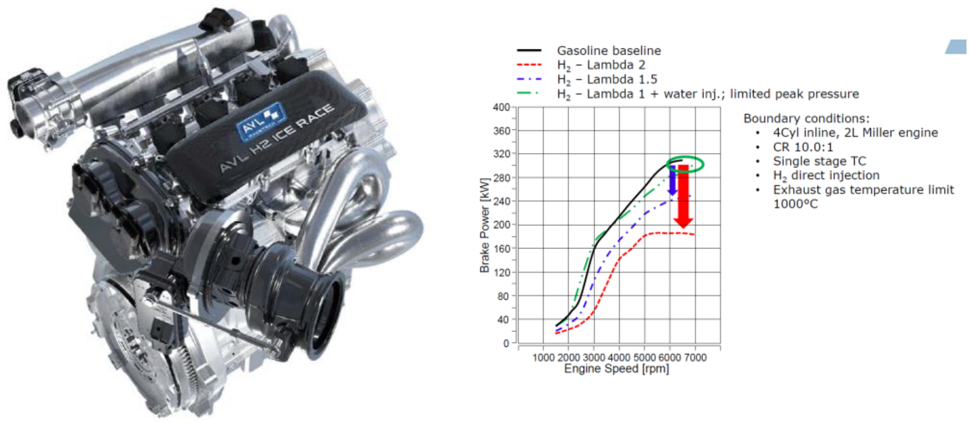

Figure 7 AVL H2 ICE racing engine demonstrator [62]

It is interesting to note that in Japan, Toyota is conducting similar testing of a racing H2 ICE but with a completely different idea and goal in mind. Toyota has been competing using a hydrogen-engine car (racing version of Corolla model) since 2021. As a first step, they used almost the exact version of the gasoline engine (3-cylinder turbocharged 1.6-litre engine) converted to a high-pressure DI hydrogen engine with hydrogen stored in a gaseous state in high-pressure tanks. Having in mind H2 ICE as the potential passenger car powertrain of the future, as a viable and more cost-effective option to a fuel cell, Toyota focused on solving the problem of onboard storage of sufficient amounts of hydrogen and therefore introduced liquid hydrogen storage in a racing car. However, their approach initially differs largely from the concept BMW introduced in the Hydrogen 7 project since it initially aimed to deliver the engine hydrogen at pressures needed for a high-pressure DI. So, Toyota's concept of liquid hydrogen storage is upgraded with a cryogenic high-pressure pump to raise the hydrogen pressure to 100 bar before evaporation and further transport to the engine injection system (***Figure 8***) [83]. Although Toyota deals with common problems like hydrogen boil-off, the size of the tank, and its design, the focus is on testing components and making progress in every aspect, mainly component durability and reliability. One of the crucial challenges is a cryogenic hydrogen pump with a plan to implement a pump with a superconducting drive. It is obvious that all efforts are being made toward exploring and finding solutions to overcome current limits in the implementation of hydrogen in both fuel cell and ICE-based passenger cars since hydrogen is seen as a critical enabler of the future carbon-neutral society in Japan [84]. The impression that engine efficiency is not in focus at the moment is only a misjudgment since Toyota's research in H2 ICE almost 14 years ago already demonstrated remarkable results in achieving high efficiencies with a goal to achieve H2 ICE efficiency at the level of state-of-the-art fuel cells. Research on a diesel-like engine geometry demonstrated the possibility of achieving an efficiency of 51% at part load with further potential of achieving similar eficinecies on higher loads by implementing a concept of spark assisted diffusive combustion with late injection strategy, injection concept which will minimise heat losses by limiting hydrogen jet penetration and wall interaction and application of largely humidified EGR [67].

A second worth-to-mention H2 ICE demonstrator is recently presented AVL heavy-duty hydrogen engine. Without any doubt, H2 ICE will be seen as a serious option for powering heavy-duty segments in the near future. The

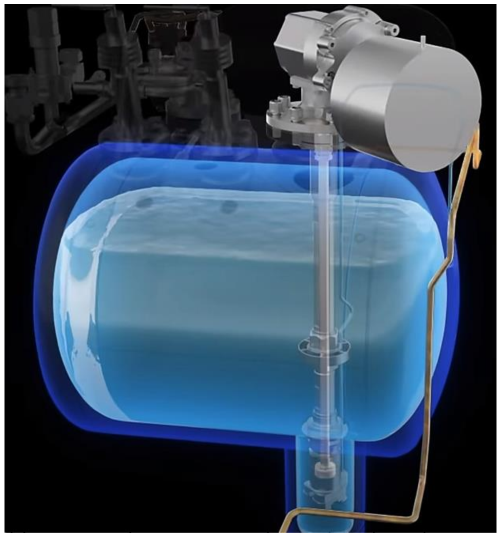

Figure 8 Toyota GR Corolla with lately introduced liquid hydrogen storage with cryogenic pump [83]

Demonstrator is a typical HD (truck 12.8 litres engine) derived from a natural gas-fueled engine. After conversion to hydrogen, the engine demonstrated performance comparable to a diesel engine of the same size with a power level of 350 kW, maximum load at 24 bar BMEP, and efficiency (BTE) of 43% (***Figure 9***). As a demonstrator, the engine is equipped with both a PFI and low-pressure DI injection system. In order to limit NOx emission, an air excess ratio of λ=1.8 is used at the highest loads while leaning the mixture toward lower loads (up to λ=2.4). A lean operation, even at λ=1.9, showed a significantly slower response on transient operation with a single-stage turbocharger and adding an e-booster or two-stage turbocharger is proposed for getting transient response behaviour comparable to a typical diesel engine (***Figure 10***).

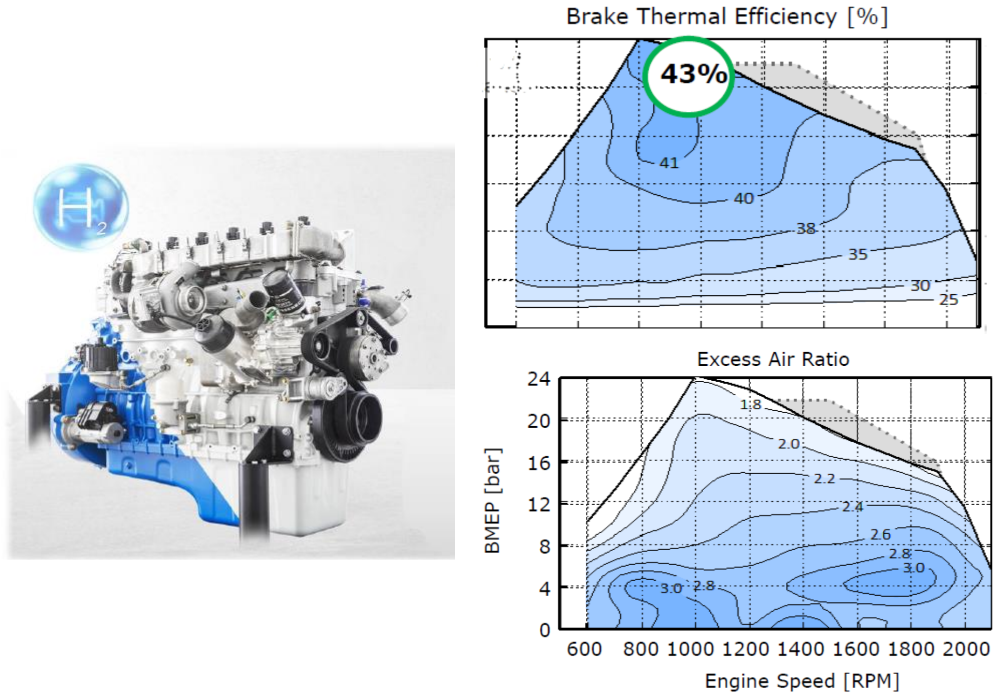

Figure 9 AVL HD H2 ICE demonstrator [69]

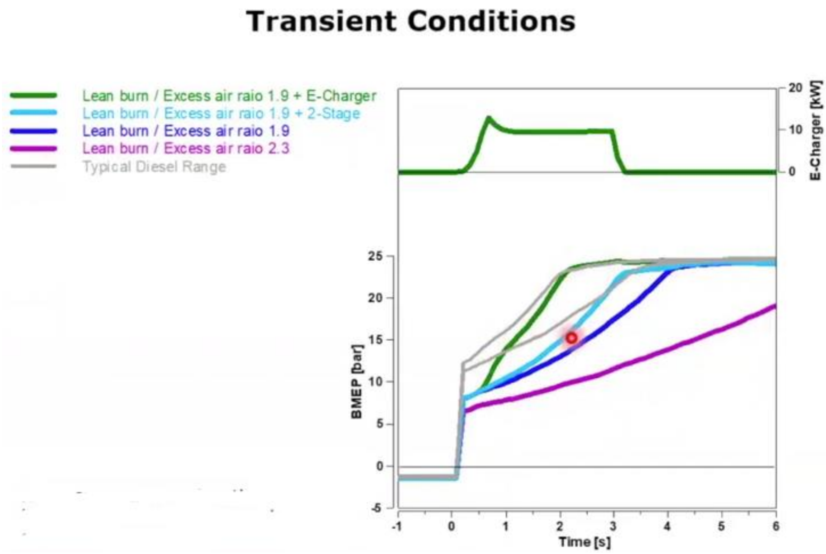

Figure 10 AVL HD H2 ICE demonstrator – air excess ratio dependable transient response and proposed solutions [69]

ICE Department of the Faculty of Mechanical Engineering of the University of Belgrade (UB FME ICED) recently (2023) upgraded its laboratory with a gaseous hydrogen supply facility and also started intensive research on controlling the modalities of the hydrogen combustion process on an adapted single-cylinder engine. The setup with a moderate high compression ratio gasoline-like engine in combination with high-pressure direct injection showed that efficiencies of 41% are achievable with the lean operation even without deep and thorough optimisation, signalling a lot of potential for extending efficiencies even higher.

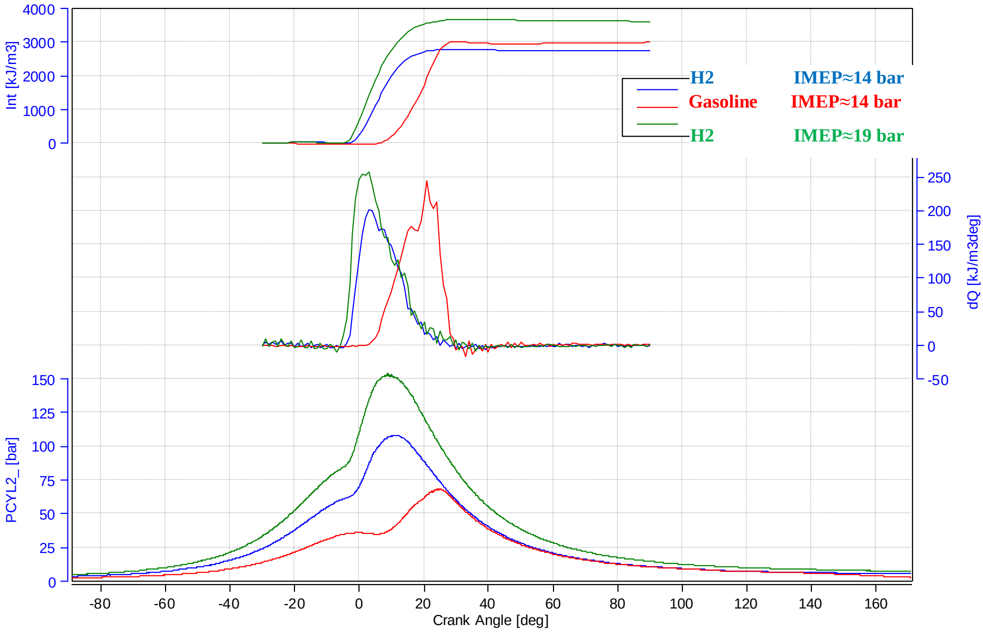

Figure 11 A comparison of H2 and gasoline ICE operation (CR=13.7, IMEP≈ 14 bar) @ UB FME ICED

Figure 11 presents a few ICE operation points measured at UB FME ICED Lab within a research area currently being conducted. Two operating points are selected for comparison – gasoline stoichiometric and lean H_2 operation with λ=2, both with high-pressure direct injection. Both operating points were conducted on a similar engine configuration (compression ratio 13.7) and at a similar load (≈14 bar IMEP). Clearly, the heat release rate and combustion speed of a lean hydrogen operation even outvies those of stoichiometric gasoline. While the spark advance of the gasoline operation has to be a result of a strong compromise toward the close knock limit (***Figure 12***), the spark advance of the lean hydrogen operation can be set at the optimal position for achieving high efficiencies i.e. MFB50 angular position for the gasoline operation is heavily retarded (MFB50=18 deg CA), while for H2 operation MFB50 can be positioned at 8 deg CA without any problem. Consequently, H2 operation easily achieves an efficiency of 40% - 7% higher than gasoline operation. Additionally, the third operational point shown is an operation on hydrogen on even higher loads (19 bar IMEP) with no evidence of irregular combustion and the same possibility for advancing the spark ignition for the best efficiency (achieved 41 %). Of course, lean operation on H2 required higher boosting pressures, i.e. 0.9 bar (relative) vs. 0.44 bar for stochiometric gasoline. At the same time, controllable and efficient, high loads with lean hydrogen operation can be achieved only at the expense of higher boosting pressure. A boosting pressure of 1.5 bar was needed for the highest load shown.

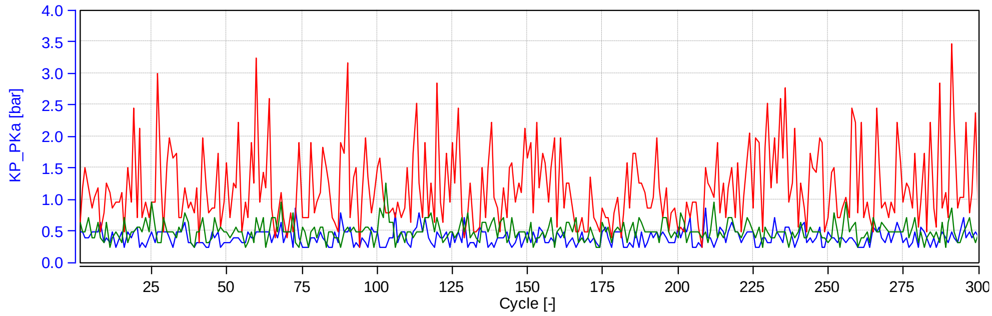

Figure 12 The maximum value of pressure deviation KP_PK (Knock Peak) for operating points from Figure 11

4 CONCLUSION

The ongoing EU Green Deal agenda implies that the IC engine has become obsolete. However, technological breakthroughs in achieving high efficiencies have positioned H2 ICE as a powertrain solution that has the potential to contribute significantly to the process of decarbonisation. Due to an onboard hydrogen storage limitation (still not efficiently solved), H2 ICE will likely not be seen as a part of the powertrain in LDVs in Europe beyond 2035. However, this is less likely to be the case in the rest of the world (particularly Japan).

In HDVs, H2 ICE is seen as a strong competitor to fuel cell-based powertrains, particularly in heavy trucks and non-road machinery powertrains.

It is also important to stress the fact that the production costs of a long-range battery vehicle are almost 2.5 times higher than those with a conventional ICE, which hugely influences the automotive industry's profit margin [85], [86]. This is also a significant motivating factor for the automotive industry to continue with the further development of ICE toward a viable, highly efficient powertrain solution that will be competitive enough in the upcoming decades.

ACKNOWLEDGMENTS

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