

## Hydrogen as an Energy Storage Solution for Ics Engines: Enhancing Efficiency and Reducing Emissions

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### Abstract

The use of oxyhydrogen-enhanced combustion in SI engines is explored in this experimental study as a potential method for improving fuel utilization, efficiency, and emissions reduction. The main goal is to lay the groundwork for the use of renewable hydrogen-based enhancement fuel in future engine designs. The experiment examines the impact of hydrogen enrichment on SI engine performance, fuel consumption, emissions, and thermal efficiency under loaded conditions, using both lean and rich mixtures of petrol-hydrogen gas. The combustion of a mixture of petrol, oxyhydrogen, and air in an SI engine cylinder is investigated, with a focus on the role of hydrogen molecules, mixture composition, and chemical properties. The addition of oxyhydrogen to the gasoline-air mixture initiates an active chemical reaction, highlighting its significance as a reactant and additional fuel component. To establish meaningful correlations, the study proposes investigating various hydrogen-gasoline ratios to determine the optimal fuel mixture for both rich and lean combustion while considering any limitations. This comprehensive approach aims to enhance our understanding of hydrogen-enhanced combustion behavior in gasoline engines, paving the way for the development of more efficient and environmentally friendly engine technologies.

**Keywords:** Emissions; Fuel blend; Oxyhydrogen; Performance & Optimal fuel mixture

### Introduction

In the global pursuit of sustainable and efficient energy storage solutions, the transition towards a cleaner and more resilient energy future is imperative [1]. As we navigate the complexities of energy demands and environmental sustainability, hydrogen energy storage has emerged as a promising candidate. This research delves into the innovative application of hydrogen energy storage in internal combustion engines (ICEs), with a specific focus on enhancing engine

performance while simultaneously mitigating harmful emissions [2].

The transportation sector, heavily reliant on internal combustion engines, remains a significant contributor to global greenhouse gas emissions and air pollution. Several investigators have suggested

utilizing hydrogen to fuel internal combustion engines as an immediate to mid-term option to start the shift toward a hydrogen infrastructure and to solve some of the challenges linked to hydrogen [3]. Numerous studies on hydrogen-powered engines and automobiles have been produced, and both

American and international corporations have been actively engaged in this field of research and development. Despite advancements in electric vehicle technology, internal combustion engines continue to dominate the market due to their established infrastructure, cost-effectiveness, and versatility [4] [5]. Therefore, it is crucial to explore methods that can improve the efficiency and environmental footprint of these engines. One such method is the integration of hydrogen as a supplementary fuel source [6].

Hydrogen, with its high energy density and clean-burning properties, presents a compelling case for its use in ICEs. This research explores the concept of on-board hydrogen generation as an additive to conventional fuels. The primary objective is to improve combustion processes and reduce overall fuel consumption, leading to enhanced engine performance and reduced emissions. By incorporating power-generating devices, reverse fuel cells, and reformers, we can convert backup DC electric supply into hydrogen-containing mixtures, such as HHO (a mixture of hydrogen and oxygen gases). These hydrogen-rich mixtures, when

introduced into the combustion chamber, have the potential to significantly boost engine performance [7].

The utilization of hydrogen in internal combustion engines is not without its challenges [8]. High-pressure hydrogen storage, safety concerns, and the need for efficient onboard hydrogen generation systems are critical considerations [8]. This paper emphasizes the significance of direct injection technology in hydrogen combustion engines [9]. Direct injection allows for precise control over the fuel-air mixture, maximizing engine efficiency and power density [10]. Despite the challenges associated with high-pressure hydrogen supply, direct injection remains a promising solution to optimize the combustion process and harness the full potential of hydrogen as a fuel.

Furthermore, highlights the environmental benefits of hydrogen energy storage in ICEs. Hydrogen combustion produces water vapour as the primary byproduct, significantly reducing the emission of pollutants such as carbon dioxide, nitrogen oxides, and particulate matter [11]. By integrating hydrogen into ICEs, we can achieve the dual benefit of maintaining the versatility and reliability of conventional engines while moving towards a cleaner and more sustainable energy solution.

This brief overview lays the foundation for a thorough investigation of hydrogen energy storage technologies in internal combustion engines. The subsequent parts of this study will look at the technical features of on-board hydrogen generation, the integration of power-generating devices and reformers, and the use of direct injection technology. By tackling these critical areas, we want to pave the path for more ecologically friendly and efficient internal combustion engines, helping to ensure a sustainable energy future.

### COMBUSTION STOICHIOMETRY

To determine the correlation involving the composition of a combustibility mixture's reacting agents (fuel and air) variable the balance of the supplies, the air input and fuel supply rates must be measured.

The ratio of the air mass flow rate  $m \cdot a$  to the fuel mass flow rate  $f \cdot m$  is called the air fuel/ratio.

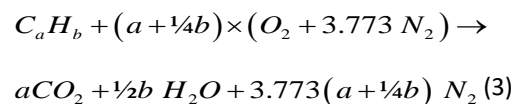
$$Air / fuel_{ratio} (A / F) = m \cdot a / f \cdot m \quad (1)$$

There is also the inverse of the above term, namely the fuel/air ratio (F/A).

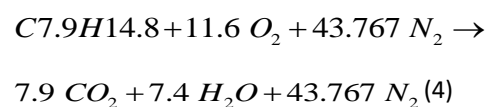
$$Fuel / Air_{ratio} (F / A) = f \cdot m / m \cdot a \quad (2)$$

A typical SI engine operating on petrol fuel usually has a range of operation of  $12 < A/F < 18$ .

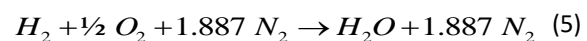
To determine the relationship between the reactant and product compositions is the conservation of mass for each of the chemicals in the reactants, the relative elemental composition of the fuel, and the respective amounts of fuel and air. A hydrocarbon fuel can undergo total oxidation if there is enough oxygen present. After that, the hydrogen in the fuel is transformed into water (H<sub>2</sub>O) and the carbon into carbon dioxide (CO<sub>2</sub>). The typical formula for one mole of hydrocarbons to burn completely in air is:



The stoichiometric (theoretical), proportions of fuel and air are given by this equation. In other words, there's just enough air to completely oxidize the petrol. The chemical composition of the fuel affects the stoichiometric air/fuel or fuel/air ratios. The equations for gasoline (C<sub>7.9</sub>H<sub>14.8</sub> is an acceptable estimate) become:



Whereas for hydrogen H<sub>2</sub> it is:



Atomic hydrogen, atmospheric nitrogen, oxygen, and carbon have molecular weights of 1.008, 12.001, 28.16, and 32, respectively. Equation (2) may be simplified by substituting  $y = b/a$ .

This yields the following expression:

$$(A / F) s = (F / A) s - 1 = 34.56(4 + y) / (12.011 + 1.008y) \quad (6)$$

$$\begin{aligned} \text{Petrol} &= C7.9H14.8 \quad (A/F)_s = 14.6 \\ \text{Hydrogen} &= H_2 \quad (A/F)_s = 34.3 \end{aligned}$$

It is feasible to burn fuel-air mixes that include more or less of the stoichiometric air required. When there is fuel-lean combustion or surplus air, the extra air remains in the products unaltered. When fuel-rich combustion occurs with less air than the stoichiometric need, there is not enough oxygen present to completely oxidize the fuel. The end products include a combination of H<sub>2</sub>O and CO<sub>2</sub>, together with N<sub>2</sub> and carbon monoxide (CO). An element balance by itself is insufficient to establish the composition of the final product; other assumptions on the chemical makeup of the product species must be made. The ratio of the actual fuel/air ratio to the stoichiometric ratio (or its inverse) is a more informative parameter for defining mixture composition because the composition of the combustion products differs significantly between fuel-rich and fuel-lean mixtures and because the stoichiometric fuel/air ratio depends on the fuel composition. The air/fuel equivalency ratio, or  $\phi$ :

$$\text{Fuel / Air}_{\text{equivalence ratio}} \phi = (F/A)_{\text{actual}} / (F/A)_s \quad (7)$$

The inverse of  $\phi$ , the relative air/fuel ratio  $\lambda$ ,

$$\begin{aligned} \text{Relative Air / Fuel ratio } \phi^{-1} &= \lambda \\ \lambda &= (A/F)_{\text{actual}} / (A/F)_s \quad (8) \end{aligned}$$

For fuel-lean mixtures:  $\phi < 1, \lambda > 1$

For stoichiometric mixtures:  $\phi = \lambda = 1$

For fuel-rich mixtures:  $\phi > 1, \lambda < 1$

In practice, the composition of the combustion products does not occur as in (2), even in cases of considerable air conditioning. Significant dissociation between CO<sub>2</sub> and H<sub>2</sub>O takes place at standard combustion temperatures. The pace at which the product gases cool determines whether recombination at low temperatures changes the product composition to what these general chemical equilibrium equations predict

### Methodology

The method of investigation aims to verify that nitrogen oxides, carbon dioxide, carbon monoxide,

and hydrocarbons are reduced in a SI engine by analysing the effects of substituting certain gasoline and oxygen mixes with their ideal mixtures. The apparatus for the experiment included a portable electric generator set with a capacity of 3 kW, coupled with instruments for measuring air temperature, load banks, and gas analysers. The engine's fuel delivery system was altered to accommodate the usage of gasoline and oxyhydrogen blends. The test engine was equipped with an electrical circuit with a variable power load to enable engine power variation managed by load switches. In the experiment, a combination of different engine load values is utilized to determine engine efficiency and pollutant emissions to evaluate petrol and oxyhydrogen fuel blends.

An extensive examination of the gasoline fuel system was conducted. After using just pure gasoline from the engine's fuel tank, the engine ran for three to five minutes to reach a steady state. The engine's throttle was fully opened to guarantee that the maximum RPM speed was reached before the generator was set up and enabled an enhanced gasoline fuel supply to the test generator engine. The engine running at full speed was selected as the standard to evaluate the differences between gasoline and oxygen performance. The Spark ignition engine experiment used a range of loads from 0W to 1000W, considering that these engines are mainly intended for small-scale personal applications with normal loads. The engine functioning at maximum speed was selected as the standard by which to evaluate the differences between gasoline and oxygen performance. Since Spark ignition engines are generally intended for small-scale personal applications with average loads lying between 400 and 600 watts, a range of loads, from 0 to 1000 watts, was used in the experiment. The schematic diagram of the experimental setup is displayed in **Figure 1**. The entirety of the information that was gathered, such as engine speed, housing and exhaust temperature, voltage, current, and concentrations of emissions, was noted once the engine reached a steady-state condition for every set of load levels. Subsequently, the loads are applied to the experimental setup, and the electric lamps are turned on and off via the load panel.

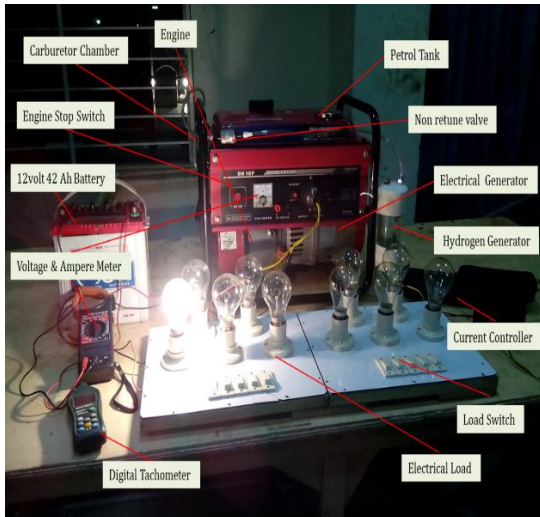


Figure 1 Pictorial View of Experimental Setup.

We can get the values of  $\text{NO}_x$ ,  $\text{CO}_2$ ,  $\text{CO}$ , and hydrocarbons for petrol, oxyhydrogen, and mixes at various loads by using a multigas analyzer. The fuel systems for gasoline underwent the following test. The engine's performance was then examined by adding various load levels to the load system. Following that, all data were collected for each set of load levels in a steady state. Following the collection of pertinent data, an analysis was conducted to compare the performance of fuel systems using petrol. All information is gathered using a multigas analyzer to compare the performance of petrol, Oxyhydrogen, and their combination up to 18 parts per million. Subsequently, the identical protocol was executed for the gasoline and oxygen blends, varying in blend engine values from 8PPM to 16PPM. The performance of the engine and the electric generator was then calculated by adding varied sets of loads to the experimental systems. Once more, the data are captured at a steady state for every set of load values. The line diagram of the experimental setup utilized in the experiment is shown in **Figure 2**.

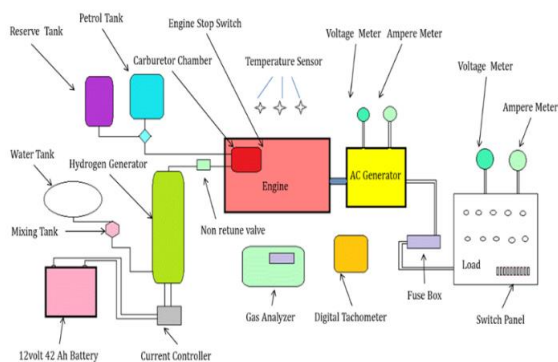


Figure 2 Line Diagram of the Experimental Setup

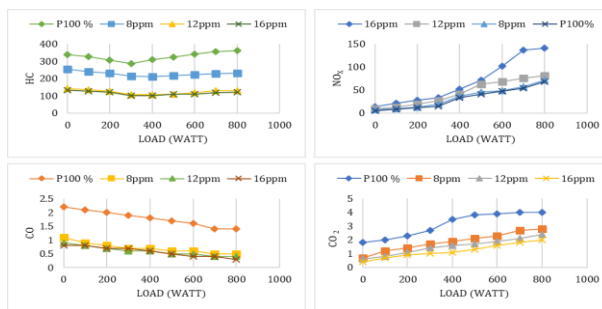
### Result And Discussion

Experiments were conducted on SI Engine using petrol, Oxyhydrogen and its blend as fuels. At steady state conditions and constant room temperature, several mixtures of gasoline and oxygen are evaluated. Major characteristics are calculated and compared for both fuels at normal load variation to maximum load, including engine and electric generator performance concerning exhaust gas temperatures, electric efficiency, and emissions ( $\text{NO}_x$ ,  $\text{CO}_2$ ,  $\text{CO}$ , and  $\text{HC}$ ). The data that was captured was used to create the accompanying graphics results. Under no load conditions and an 800-watt electrical load at various load ranges. The results of  $\text{NO}_x$ ,  $\text{CO}_2$ ,  $\text{CO}$ , and  $\text{HC}$  are obtained. We displayed each blend with a certain Oxyhydrogen and gasoline combination as 8PPM, 12PPM, 16PPM, and pure petrol, respectively, for comparison graphs depicted.

As the percentage load rises, so do the nitrogen oxides. With a tiny amount of nitrogen dioxide ( $\text{NO}_2$ ), nitrogen oxide ( $\text{NO}$ ) will make up the majority of this.  $\text{NO}_x$  is a very unwanted gas. At low temperatures, stable diatomic nitrogen molecules ( $\text{N}_2$ ) can be found in the atmosphere. As a result, extremely minute trace levels of nitrogen oxides are discovered. Greater dissociation and the formation of more  $\text{NO}_x$  occur at higher temperatures during the combustion event. In addition to the high flame temperature at this point, there is also an abundance of oxygen that may react with nitrogen to produce a variety of oxides. The length of the combustion process has a big impact on how much  $\text{NO}_x$  forms inside the cylinder [12]. The amount of  $\text{NO}_x$  increases with the proportion of hydrogen mix. This is due to the fact that a higher hydrogen mix will raise the temperature at which hydrogen burns and expand its range of flammability. As can be seen below, **Figure 3** illustrates that the nitrous oxide content is highest for a 16PPM hydrogen blend and lowest for gasoline.

A rise in the percentage load is accompanied by an increase in carbon monoxide. Some fuel does not burn and some carbon turns into  $\text{CO}$  when there is not enough oxygen to convert all of the carbon to  $\text{CO}_2$ .  $\text{CO}$  is seen as an unwanted emission in addition to being a wasted chemical energy [13]. Rich running is when an engine produces the most  $\text{CO}$ . It takes a

rich mixture to ignite or accelerate when under load. Incomplete combustion, localized rich patches, and poor mixing will also contribute to CO emissions. However, carbon monoxide will decrease as the ratio of hydrogen mix rises. The engine won't be able to effectively burn through all of the petrol. The sump will contain lubricating oil, which raises the level of carbon monoxide. As the blend of hydrogen increases, the flow rate of gasoline is gradually reduced [14]. This results in a shorter post-combustion phase than gasoline, which lowers the amount of time and cylinder temperature required for the CO oxidation process and slows the rate at which CO turns into CO<sub>2</sub>. The lower CO is caused by hydrogen's greater spectrum of flammability. As may be seen below, **Figure 3** CO emissions are highest for gasoline and lowest for a 16PPM hydrogen combination.

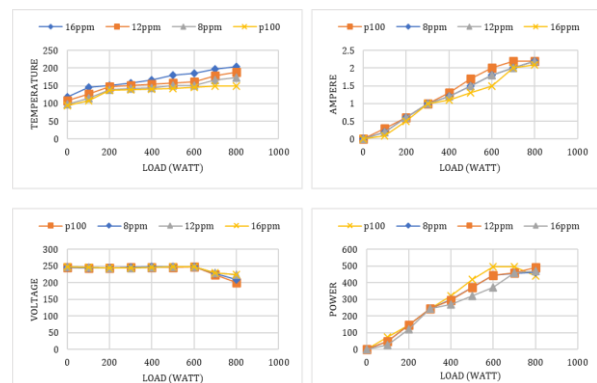


**Figure 3 Emission of NO<sub>x</sub>, CO<sub>2</sub>, CO & HC at variable load**

The amount of unburned hydrocarbon increases with the percentage load. Due to there isn't enough oxygen in a fuel-rich combination for all the carbon to react with, the exhaust products have high concentrations of CO and HC. This is especially true during the beginning when a deliberately rich air-fuel combination is used. A smaller degree of this is also true while accelerating quickly when under load. Poorer combustion happens when the air-fuel ratio is too low, which again results in HC emissions [15]. Due to sporadic partial burning cycles, combustion quality drastically deteriorates when the lean flammability limit is approached and HC emissions start increasing once more. It is also observed that adding hydrogen lowers the emissions of hydrocarbons. The fact that hydrogen has a shorter quenching distance than gasoline is one of the factors contributing to the reduction in HC emissions

caused by hydrogen addition [16]. The flame may go closer to the cylinder wall with a shorter quenching distance, which promotes full combustion [17]. Another explanation is that hydrogen has a high diffusivity, which makes it easier for it to diffuse into the atmosphere and promotes the production of a more homogeneous and consistent fuel-air combination [18]. Furthermore, the rapid flame speed of hydrogen shortens the time needed for combustion and lowers the likelihood that incomplete and slow-burning combustion cycles will occur. The 16PPM hydrogen mix has the lowest HC emission in **Figure 3**, whereas gasoline exhibits the greatest emission.

As the temperature of the exhaust gas rises, so does the electrical demand. The reason the electrical generator set's speed drops with increasing load. In spark ignition engines, the air and fuel combination ignite through the spark plug before spontaneous ignition may happen because of low compression ratios and, consequently, low temperatures at the end of compression. To ensure that the whole mixture is ignited, SI engines are made to allow a flame front to spread smoothly from the spark plug into the unburned mixture. The fuel's chemical energy is released as the flame front advances, raising the temperature and pressure of the combustion gases behind it. The unburned mixture, sometimes known as the end gas, is compressed and heated as the front moves forward. However, the governor's existence causes the speed to mostly stay constant. Therefore, the mass flow rate of the gasoline rises to maintain the speed. The wide range of flammability and efficient burning of hydrogen, as seen in Figure 4, will cause the temperature of the exhaust gas to rise when hydrogen is present.



**Figure 4 Exhaust gas temperatures at variable load**

If the electric generator behaviour depicted in **Figure4** above is followed, petrol and hydrogen mixes will be used in the experimental setup. Electric generator performance is improved concerning load and mixes; a higher concentration of oxyhydrogen boosts the generator's efficiency in the 16PPM oxygen supply.

### Conclusions

The goal of this research was to determine the best blend of Oxyhydrogen-gasoline fuel combination with the lowest emissions. In SI engines, it is more feasible to blend gasoline and oxygen than to utilize gasoline alone. It is necessary to assess the engines' performance and emission characteristics before employing these mixes. To assess performance and exhaust emissions for different gasoline concentrations that include oxyhydrogen addition in the engine, an experimental study was conducted.

Based on experimental findings, when an ideal blend of petrol and oxyhydrogen was used, the engine's output torque increased marginally, the leaning effect of the oxygen addition resulted in a dramatic decrease in CO and HC emissions, and the improved combustion led to an increase in CO<sub>2</sub> emissions. Depending on the engine settings, CO and HC emissions were reduced by around 8PPM and 12PPM, respectively, but CO<sub>2</sub> emissions increased by 8PPM. Furthermore, it has been noted that a low percentage of petrol/oxygen hydrogen mixes may be utilized in SI engines without the need for modification. Blended gasoline with oxygen hydrogen may reduce CO and HC emissions. The most intriguing finding is that adding kerosene to gasoline enhances cold start performance for SI engines and greatly reduces CO and HC emissions. As the number of oxygen-hydrogen mixes increases, so does the electric generator's performance.

### Future Scope

For the optimization of the emission rate of hydrocarbon, we can go for an internal exhaust recirculate system employing engine modification. In this setup Load, Thermal Analysis & Emission rate at different blends of Hydrogen and pyro oil can be done.

### References

1. Sikiru, Surajudeen, et al. "Hydrogen-powered horizons: Transformative technologies in clean energy generation, distribution, and storage for sustainable innovation." *International Journal of Hydrogen Energy* 56 (2024): 1152-1182.
2. Ekechukwu, Darlington Eze, and Peter Simpa. "A comprehensive review of innovative approaches in renewable energy storage." *International Journal of Applied Research in Social Sciences* 6.6 (2024): 1133-1157.
3. Habib, Mohamed A., et al. "Hydrogen combustion, production, and applications: A review." *Alexandria Engineering Journal* 100 (2024): 182-207.
4. Arora, Divyanshu, and Rajesh Kumar Arora. "Study of electric vehicle (EV) technology & advancement." *Water and Energy International* 66.10 (2024): 33-41.
5. Shahzad, Khurram, and Izzat Iqbal Cheema. "Low-carbon technologies in automotive industry and decarbonizing transport." *Journal of Power Sources* 591 (2024): 233888.
6. Qureshy, Ali MMI, and Ibrahim Dincer. "A new integrated renewable energy system for clean electricity and hydrogen fuel production." *International Journal of Hydrogen Energy* 45.41 (2020): 20944-20955.
7. Algayyim, SattarJabbarMurad, et al. "Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review." *Fuel* 362 (2024): 130844.
8. Leng, Xianyin, et al. "Effects of hydrogen enrichment on the combustion and emission characteristics of a turbulent jet ignited medium speed natural gas engine: A numerical study." *Fuel* 290 (2021): 119966.
9. Park, Cheolwoong, et al. "Effect of fuel injection timing and injection pressure on performance in a hydrogen direct injection engine." *International Journal of Hydrogen Energy* 47.50 (2022): 21552-21564.
10. Hu, Zhen, et al. "High-pressure injection or low-pressure injection for a direct injection hydrogen engine." *International Journal of Hydrogen Energy* 59 (2024): 383-389.

11. Goren, A. Yagmur, et al. "Recent developments on carbon neutrality through carbon dioxide capture and utilization with clean hydrogen for production of alternative fuels for smart cities." *International Journal of Hydrogen Energy* 79 (2024): 551-578.
12. Doppalapudi, Arun Teja, and Abul Kalam Azad. "Advanced Numerical Analysis of In-Cylinder Combustion and NOx Formation Using Different Chamber Geometries." *Fire* 7.2 (2024): 35.
13. Yu, Yang, et al. "Decomposition analysis of China's chemical sector energy-related CO2 emissions: From an extended SDA approach perspective." *Energy & Environment* (2023): 0958305X231151682.
14. Purayil, S. T. P., et al. "Review of hydrogen-gasoline SI dual fuel engines: Engine performance and emission." *Energy Reports* 9 (2023): 4547-4573.
15. Kraus, Christoph, et al. Highly efficient and clean combustion engine for synthetic fuels. No. 2023-01-0223. SAE Technical Paper, 2023.
16. Algayyim, SattarJabbarMurad, et al. "Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review." *Fuel* 362 (2024): 130844.
17. Gu, Wu, et al. "Applications of PLIF in fundamental research on turbulent combustion of hydrogen and hydrogen hybrid fuels: A brief review." *International Journal of Hydrogen Energy* 78 (2024): 1240-1274.
18. Giacomazzi, Eugenio, et al. "Hydrogen combustion: features and barriers to its exploitation in the energy transition." *Energies* 16.20 (2023): 7174